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FOR THE PROJECT

"RESEARCH IN

STORE AND FORWARD COMPUTER NETWORKS"

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SUMMARY

Technical Problem

The ARPA Computer Network will provide communication paths between computers distributed across the United States. The ARPA Contract with the Network Analysis Corporation involves the analysis and design of this network and the study of properties of networks of this type.

During the reporting period, the technical problems considered were the relationship between traffic, routing, throughput and cost. The main problems were to determine the effect of routing on network throughput and to study the properties of large store-and-forward networks.

General Methodology

The general approach to the above problems was to develop a powerful set of computer programs to optimize computer network cost and performance. The programs were used to derive estimates of optimum performance for specified networks, and to derive the tradeoffs between cost and throughput as a function of the number of nodes in the network under consideration.

Technical Results

A number of important technical results were derived during the reporting period.

1. A computer program that can find optimal routes for all traffic was developed. The program was used to derive upper bounds on performance and it was shown that the methods used to design the ARPA Network yield near optimal results.

2. It was shown that the performance of the ARPA Network is highly insensitive to input traffic. Therefore, if traffic forecasts are inaccurate, the network will retain its high throughput capabilities.

3. Cost-throughput relationships were derived for networks with 20, 40, 60, 80, and 100 nodes. It was shown that large networks are economical to operate using the present technology of the ARPA Network.

Department of Defense Implications

The substantial cost advantages of computer-communication networks with as many as 100 nodes was demonstrated. This property is of particular importance in satisfying the Defense Department's computer and communication requirements. The technical results imply that large computer networks can supply rapid and economical means for resource sharing and communications.

Implications for Further Research

The use of equipment presently being developed and communication line options not yet available may further enhance

the economy of large store-and-forward networks. This area should be pursued since by using the network optimization approach, it may be possible to suggest the most efficient equipment to develop.

I. OPTIMAL ROUTING

The efficiency of any network design depends crucially on the routing procedures used in generating and operating the network. Efficient design techniques involve the repeated analysis, transformation and reanalysis of proposed starting networks. Hence, the cost required to apply a given routing procedure is a limiting factor on the potential range of applicable transformations and hence, the economy of the final network design. Therefore, network optimization requires a compromise between the effectiveness and computational complexity of the routing procedure.

The basic routing procedure employed for examining the cost-throughput characteristic of large networks and in optimizing the ARPA Network was described in References [1] and [2] and is summarized in Section 2. This suboptimal procedure, called Minimum Link Traffic Routing, has the advantage that it is inexpensive to use and gives better performance than a number of other practical routing schemes as indicated by simulation models [3]. On the other hand, there has been no clear picture of the performance losses generated by non optimal routing procedures.

In this section, we discuss a procedure for optimally routing traffic through a fixed network whose lines have been

assigned fixed capacities. The procedure is capable of determining the traffic flow pattern which minimizes average time delay. It is shown that the routing problem can be formulated as a variation of the classical "multicommodity flow" problem, whose computational complexity depends mainly on the number of nodes and links within the network. Examples of networks with twelve and eighteen nodes are examined and the results of optimal routing compared with the suboptimum procedures used in [1] and [2] and in the other parts of this report.

Problem Formulation

In a standard multi-commodity flow problem [4], a source is a node from which commodities are originated and a terminal is a node to which commodities are destined. The multicommodity problem consists of finding a flow pattern that either maximizes the amount of commodities delivered to the terminals or delivers specified amounts of commodities with least cost. In the latter case, cost is usually computed as the sum of constant cost factors for transporting each commodity through each link times the amount of commodity so transported.

The commodities are packets of data to be transmitted through the network. Each node is a terminal as well as a source. Element $r_{k,i}$ in the traffic requirement matrix R can be viewed

as the amount of commodity i which is supplied from node k destined for node i. All traffic destined for i can be viewed as commodity i. There are then N commodities where N is the number of nodes in the network. Each node demands exactly one distinct commodity and supplies N-1 others. We want to route the traffic such that the average delay time (which corresponds to the cost function) is minimized and each branch flow is less than the corresponding branch capacity. The average delay time is a non-linear function and consequently, we must solve a problem considerably more difficult than the classical multicommodity flow problem.

The model for time delay analysis has been described in [1] and [2] and will not be repeated here. Delay time is affected by both node and branch limitations. The effect of node limitations is small until the network approaches saturation [1, 2]. In order to obtain tractable results, node limitation effects were omitted from the network routing model. This was justified on the following basis:

(1) Past experience has shown that node limitations play a minor role at the traffic levels under consideration. The reason for this is that for the ARPA Network, the IMP buffers are capable of handling the required traffic.

(2) It can be shown that minimizing average time delay tends to minimize the effect of node limitations as computed by NAC's time delay analysis program. The multicommodity routing problem can then be formulated as the following separable convex [4] programming problem:

Minimize

$$\frac{1}{r}\sum_{i=1}^{M}\left[\frac{(1+\mu'/\mu_{ack})f_i/\mu'}{C_i(C_i-(1+\mu'/\mu_{ack})f_i)}+\frac{1}{\mu C_i}+d_i\,\frac{1.5}{186000}+T_{IMP}\right]f_i+T_{HOST}$$

subject to

$$A\,\underline{f}_i=\underline{r}_i \qquad \text{for } i=1,2,\ldots,N \tag{1}$$

$$\sum_{i=1}^{N} f_{i,j}-f_j=0 \qquad \text{for } j=1,2,\ldots,N \tag{2}$$

$$\underline{f}\leq\underline{c} \tag{3}$$

where

T_{HOST} is the average delay time on HOST-IMP line for an average packet

T_{IMP} is the estimated IMP processing time for an average packet

M is the number of links (each physical link is represented by two oppositely directed links)

N is the number of nodes (IMPs)

r is the total IMP-to-IMP throughput, RFNM, header, and parity check included

C_i is the capacity of link i

$1/\mu$ is the average short message length

$1/\mu'$ is the average packet length in the system including long messages, RFNM, header, and parity check

$1/\mu_{ack}$ is the packet length of an acknowledgment

d_i is the length of link i in miles

A is the incidence matrix of the network.

That is, $a_{i,j} = 1$ if link j is directed out of node i,

$a_{i,j} = -1$ if link j is directed into node i and

$a_{i,j} = 0$ if link j is not incident at node i.

f_i is the flow in link i

$f_{i,j}$ is the portion of the traffic on link j that is destined for node i

$\underline{f}_i$ is the transpose of the vector $(f_{i,1}, f_{i,2}, \ldots, f_{i,j}, \ldots, f_{i,m})$.

$\underline{f}$ is the transpose of $(f_1, f_2, \ldots, f_M)$.

$r_{i,i}$ is the negative of the total traffic destined for (or required at) node i.

$r_{i,j}$ for $i \neq j$ is the traffic generated at node j with final destination node i.

$\underline{r}_i$ is the transpose of the vector $(r_{i,1}, r_{i,2}, \ldots, r_{i,j}, \ldots, r_{i,M})$.

$\underline{C}$ is the transpose of the vector $(C_1, C_2, \ldots, C_M)$.

In the objective function, the first term in the bracket is the average waiting time and the second term is the average transmission time required for a short message to travel across link i; the third term is the propagation time on that link. The factor $(1 + \mu'/\mu_{ack})$ is used to compensate for the extra traffic due to acknowledgments. (This compensation approach is only applicable with a symmetric traffic matrix as is our case). The objective function is convex as is easily seen by rewriting it as

$$\frac{1}{r}\sum_{i=1}^{M}\left[\frac{1/\mu'}{C_i - f_i} + \left\{\frac{1}{C_i\mu} - \frac{1}{C_i\mu'} + \frac{1.5}{186000}\ d_i + T_{IMP}\right\}\right] f_i + T_{HOST},$$

where f_i has replaced $(1 + \mu'/\mu_{ack})f_i$, and r has replaced $(1+ \mu'/\mu_{ack})r$. Thus, it can be approximated with arbitrary accuracy by a monotonic, piecewise linear continuous function of the $\{f_i\}$. The accuracy of the approximation is determined by the number of line segments used.

Constraint (1) is called the conservation constraint and represents the requirement that the flow into any IMP is equal to

the flow out of any IMP. The second constraint merely indicates that the flow in any link is equal to the sum of all commodities in that link. Constraint (3) restricts the traffic on any link to be no greater than the corresponding link capacity.

If the objective function is approximated by a piecewise linear one, the routing problem can be solved as a linear program. Then, the limitation to the solution of specified routing problem is its size and computational complexity.

The number of constraints in the linear program is in part a function of the accuracy with which the objective function is approximated. If P linear segments are used in the approximation, then the program has $N^2 + 3M$ constraints and $(N + P + 1)M$ variables.

The desired output is a curve indicating the relationship between time delay and input traffic. The linear program formulated above will produce one value of the objective function (minimum delay) for a specified value of input traffic. Because of the large fixed overhead involved in setting up and finding an initial feasible solution for the linear program, the cost of generating a curve by repetitive application of a linear programming algorithm would be prohibitive on a point by point basis. Instead, a parametric approach can be used. Constraint (1) is written as

$$A \underline{f}_i = \underline{r}_i + \theta \underline{r}_i \quad \text{for } i = 1, 2, \ldots, N$$

Initially, $\theta = 0$. The linear program is solved and the basis for the optimal solution retained. The value of θ is then increased. This, in effect, increases the specified traffic matrix. The parameter θ is continuously increased until a basis change is required for a new feasible solution. A new optimal solution is then found by generating a feasible solution by starting from the basis of the previous optimal solution. The process terminates when θ reaches a preset upper limit or when feasible solutions can no longer be found for higher values of θ. The effect of the parameterization is to generate the entire curve relating time delay to traffic at a substantially reduced cost.

Examples

Several examples of the problem were solved in the above manner. In addition to computing the minimum time delay for each traffic-matrix, the paths found by the program in generating this time delay were recorded. These paths were then compared with those found by Minimum Link-Traffic Routing. In addition, time delays for both routing procedures were compared. From these examples, the following results were found:

(1) The Minimum Link Traffic Routing algorithm is only slightly inferior to the theoretically

best routing procedure especially in high traffic situations;

(2) Although an optimal routing can use many paths to satisfy the flow requirement between any pair of nodes, in the solutions examined thus far a single path between most pairs of nodes is used;

(3) Most routes picked by the optimal routing are the same as those determined by the Minimum Link Traffic Routing;

(4) While the Minimum Link Traffic Routing uses the same routes regardless of the traffic level, routes picked by the optimal routing vary somewhat with the traffic level.

One network considered is shown in Figure 1.1. A uniform traffic matrix was used. The network's adjacency matrix and capacity matrix are given in Table 1.1. The fifth row of Table 1.1a indicates that node 5 is connected to node 7 and node 9. The fifth row of Table 1.1b indicates that the capacity of the branch connecting node 5 and node 7 is 230,400 bits/sec, and the capacity of the branch connecting node 5 and node 9 is 50,000 bits/sec. Other rows in this table can be interpreted in the same way. The average delay times

arising from different traffic levels are shown in Table 1.2 and 1.3 and plotted in Figure 1.2. Table 1.4 shows the routes adopted by the Minimum Link Traffic Routing algorithm. For example, row 3 under source node 1 means that the route from node 1 to node 5 is via node 3 and node 7. Other routes can be interpreted similarly. Table 1.5 shows the routes selected for the optimal routing for the traffic at 6650 bits/node. The rows with asterisks are the routes that differ from those indicated in Table 1.4. Finally, Tables 1.6 and 1.7 show the link traffic for the optimal routing at 6500 bits/sec/node and at 8120 bits/sec/node, respectively. As an example of the interpretation of these tables, in Table 1.6 the first row indicates that the link connecting node 2 and node 1 has a total traffic of 2000 bits/sec of which 1000 bits/sec is bound for node 1 and 1000 bits/sec is bound for node 3.

The 18 node network shown in Figure 1.3 was also considered with both Minimum Link Traffic routing and optimal routing with uniform traffic. Its adjacency and capacity matrices are given in Table 1.8. Results are shown in Figure 1.4 and Tables 1.9 - 1.13.

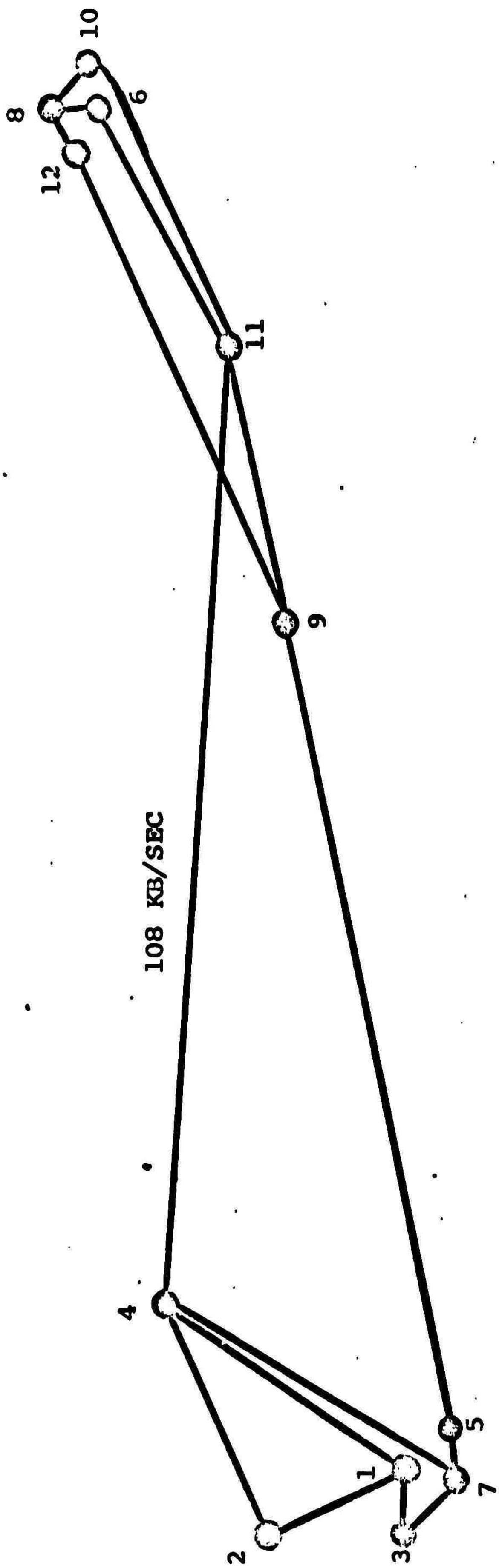
The above examples indicate that the Minimum Link Traffic Routing is very effective under uniform traffic condition. However,

since the networks used were originally designed using essentially uniform traffic assumptions, it may be possible that they are biased so that the Minimum Link Traffic Routing will give near optimum routing when uniform traffic is applied. We therefore examine the same networks with randomly generated traffic matrices. A vector of $N(N - 1)/2$ uniformly random integers is generated and the element $r_{i,j}$ of the traffic matrix R set equal to the $[\frac{(2N - j)(i - 1)}{2} \quad (j - i)]^{th}$ element in the vector multiplied by K for $i > j$, and to be $r_{j,i}$ if $i < j$. Here, K is a constant whose value determines the proper traffic level. In the 12 node network, K = 150 to give an initial traffic of approximately 5 kilobits/sec/node. In the 18 node network, K = 161 to give a starting traffic of approximately 10 kilobits/sec/node.

Time delays using both the optimum and suboptimum procedures can then be generated in the same manner as before. The new delays indicate that the networks are not uniform traffic biased. The relative performance of the Minimum Link Traffic Routing in comparison with Optimal Routing under random traffic condition is as good as that under the uniform traffic condition. (It is also interesting to note that, with the same routing procedure, the throughput under the random traffic is 10% higher in one case and 10% lower in the other.

This shows that the networks will operate properly with a non-uniform traffic matrix, even though they were originally designed under uniform traffic). The delays for the 12 node network with random traffic are shown in Figure 1.5, and Tables 1.14 and 1.15.

Finally, in Section 2, the results of a combination of simulation and analysis to determine the sensitivity of network performance to the traffic distribution is discussed.



HIGH THROUGHPUT 12 NODE NETWORK

THE 12 NODE NETWORK
USED FOR ROUTING
COMPARISON

FIGURE 1.1

TABLE 1.1

ADJACENCY MATRIX

1-	2	3	4	
2-	1	4		
3-	1	7		
4-	2	1	7	11
5-	7	9		
6-	8	11		
7-	3	5	4	
8-	6	10	12	
9-	5	11	12	
10-	8	11		
11-	4	6	9	10
12-	8	9		

(a)

CAPACITY MATRIX

1-	50000	50000	50000	
2-	50000	50000		
3-	50000	50000		
4-	50000	50000	50000	108000
5-	230400	50000		
6-	230400	50000		
7-	50000	230400	50000	
8-	230400	230400	230400	
9-	50000	50000	50000	
10-	230400	50000		
11-	108000	50000	50000	50000
12-	230400	50000		

(b)

TABLE 1.2

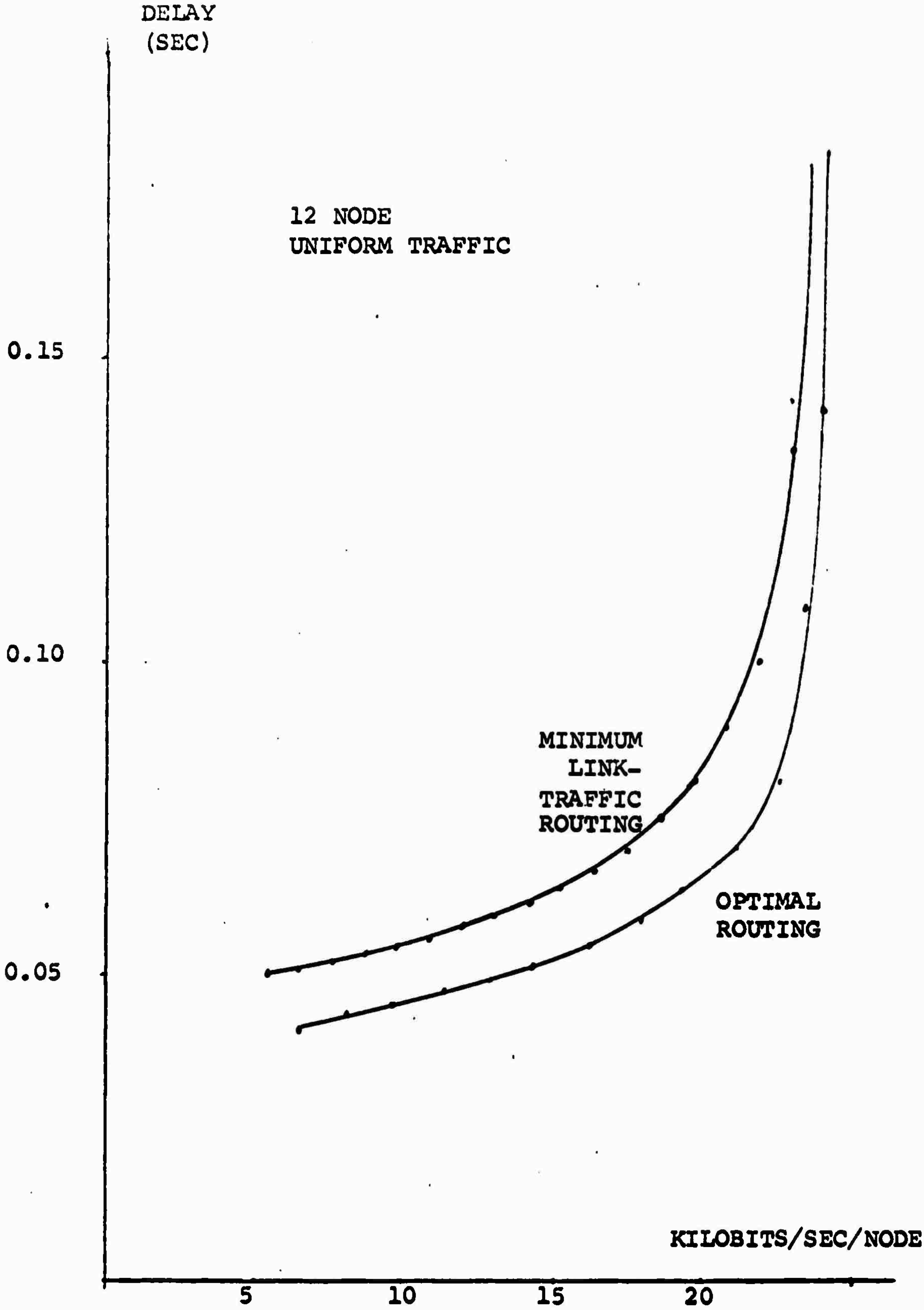
TIME DELAY ANALYSIS - MINIMUM LINK TRAFFIC ROUTING

Average No. Bits/Sec/Node	Delay (Sec)
5500	.0502
6600	.0512
7700	.0522
8800	.0534
9900	.0546
11000	.0561
12100	.0577
13200	.0595
14300	.0617
15400	.0642
16500	.0672
17600	.0708
18700	.0755
19800	.0816
20900	.0903
22000	.1044
23100	.1352
23650	.1810
24200	1.7489

TABLE 1.3

TIME DELAY ANALYSIS - OPTIMAL ROUTING

Average No. Bits/Sec/Node	Delay (Sec)
6500	0.0408
8120	0.0437
9730	0.0450
11400	0.0473
13000	0.0485
14400	0.0506
16250	0.0540
18000	0.0576
19450	0.0640
21250	0.0700
22750	0.0810
23600	0.1197
24000	0.1420


DELAY
(SEC)
12 NODE
UNIFORM TRAFFIC
0.15
0.10
0.05
MINIMUM
LINK-
TRAFFIC
ROUTING
OPTIMAL
ROUTING
KILOBITS/SEC/NODE
5
10
15
20

<u>FIGURE 1.2</u>

TABLE 1.4

MINIMUM LINK TRAFFIC ROUTES

Source Node 1

1	3	7		
1	4	11		
1	3	7	5	
1	4	11	6	
1	4	11	9	
1	4	11	10	
1	4	11	6	8
1	4	11	9	12

Source Node 2

2	1	3		
2	4	7		
2	4	11		
2	4	7	5	
2	4	11	6	
2	4	11	9	
2	4	11	10	
2	4	11	6	8
2	4	11	9	12

Source Node 3

3	1	2			
3	7	4			
3	7	5			
3	7	5	9		
3	1	4	11		
3	1	4	11	6	
3	1	4	11	10	
3	7	5	9	12	
3	7	5	9	12	8

Source Node 4

4	7	3	
4	7	5	
4	11	6	
4	11	9	
4	11	10	
4	11	6	8
4	11	9	12

Source Node 5

5	7	3		
5	7	4		
5	9	11		
5	9	12		
5	7	3	1	
5	7	4	2	
5	9	11	6	
5	9	12	8	
5	9	11	10	

Source Node 6

6	11	4		
6	11	9		
6	8	10		
6	8	12		
6	11	4	1	
6	11	4	2	
6	11	9	5	
6	11	4	7	
6	11	4	1	3

Source Node 7

7	3	1		
7	4	2		
7	5	9		
7	4	11		
7	4	11	6	
7	4	11	10	
7	5	9	12	
7	5	9	12	8

Source Node 8

8	12	9			
8	10	11			
8	10	11	4		
8	12	9	5		
8	6	11	4	1	
8	6	11	4	2	
8	12	9	5	7	
8	12	9	5	7	3

Source Node 9

9	11	4	
9	11	6	
9	5	7	
9	12	8	
9	11	10	
9	11	4	1
9	11	4	2
9	5	7	3

Source Node 10

10	11	4		
10	8	6		
10	11	9		
10	8	12		
10	11	4	1	
10	11	4	2	
10	11	9	5	
10	11	4	7	
10	11	4	1	3

Source Node 11

11	4	1	
11	4	2	
11	9	5	
11	4	7	
11	10	8	
11	9	12	
11	4	1	3

Source Node 12

12	9	5		
12	8	6		
12	8	10		
12	9	11		
12	9	11	4	
12	9	5	7	
12	9	11	4	1
12	9	11	4	2
12	9	5	7	3

TABLE 1.5

OPTIMAL ROUTES

Average No. Bits/Sec/Node = 6650

Average Delay = 0.0408

Source Node 1

	1	3	7			
	1	4	11			
	1	3	7	5		
	1	4	11	6		
	1	4	11	9		
	1	4	11	10		
	1	4	11	6	8	
*	1	4	11	6	8	12

Source Node 2

	2	1	3			
	2	4	7			
	2	4	11			
	2	4	7	5		
	2	4	11	6		
	2	4	11	9		
	2	4	11	10		
	2	4	11	6	8	
*	2	4	11	6	8	12

Source Node 3

3	1	2			
3	7	4			
3	7	5			
3	7	5	9		
3	1	4	11		
3	1	4	11	6	
3	1	4	11	10	
3	7	5	9	12	
3	7	5	9	12	8

Source Node 4

	4	7	3		
	4	7	5		
	4	11	6		
	4	11	9		
	4	11	10		
*	4	11	10	8	
*	4	11	10	8	12

Source Node 5

	5	7	3		
	5	7	4		
*	5	7	4	11	
	5	9	12		
	5	7	3	1	
	5	7	4	2	
*	5	9	12	8	6
	5	9	12	8	
*	5	7	4	11	10

Source Node 6

	6	11	4		
*	6	8	12	9	
	6	8	10		
	6	8	12		
	6	11	4	1	
	6	11	4	2	
*	6	8	12	9	5
	6	11	4	7	
	6	11	4	1	3

Source Node 7

7	3	1		
7	4	2		
7	5	9		
7	4	11		
7	4	11	6	
7	4	11	10	
7	5	9	12	
7	5	9	12	8

Source Node 8

	8	12	9			
*	8	6	11			
*	8	6	11	4		
	8	12	9	5		
	8	6	11	4	1	
	8	6	11	4	2	
	8	12	9	5	7	
	8	6	11	4	1	3

Source Node 9

	9	11	4	
*	9	12	8	6
	9	5	7	
	9	12	8	
*	9	12	8	10
	9	11	4	1
	9	11	4	2
	9	5	7	3

Source Node 10

	10	11	4		
	10	8	6		
*	10	8	12	9	
	10	8	12		
	10	11	4	1	
	10	11	4	2	
*	10	8	12	9	5
	10	11	4	7	
	10	11	4	1	3

Source Node 11

	11	4	1	
	11	4	2	
*	11	4	7	5
	11	4	7	
	11	10	8	
*	11	10	8	12
*	11	4	7	3

Source Node 12

	12	9	5			
	12	8	6			
	12	8	10			
*	12	8	10	11		
*	12	8	10	11	4	
	12	9	5	7		
*	12	8	10	11	4	1
*	12	8	10	11	4	2
	12	9	5	7	3	

TABLE 1.6

EXAMPLE OF LINK TRAFFIC IN THE OPTIMAL ROUTING

Average No. Bits/Sec/Node = 6500

Average Delay Time = 0.0408

LINK TRAFFIC FROM

LINK	TOTAL LINK TRAFFIC	NODE 1	2	3	4	5	6	7	8	9	10	11	12
(2, 1)	2000	1000	0	1000	0	0	0	0	0	0	0	0	0
(3, 1)	7000	3000	1000	0	0	0	1000	0	1000	0	1000	0	0
(4, 1)	10000	7000	0	3000	0	0	0	0	0	0	0	0	0
(1, 2)	2000	0	2000	0	0	0	0	0	0	0	0	0	0
(4, 2)	9000	0	9000	0	0	0	0	0	0	0	0	0	0
(1, 3)	7000	0	0	5000	0	1000	0	1000	0	0	0	0	0
(7, 3)	8000	2000	0	6000	0	0	0	0	0	0	0	0	0
(2, 4)	9000	0	0	0	1000	1000	1000	1000	1000	1000	1000	1000	1000
(1, 4)	10000	0	0	0	1000	0	2000	0	2000	1000	2000	1000	1000
(7, 4)	10000	0	2000	0	3000	0	1000	0	0	0	1000	3000	0
(11, 4)	[illegible]	6000	6000	3000	6000	2000	0	3000	0	0	0	0	0
(7, 5)	12000	0	0	0	0	7000	0	0	1000	2000	0	0	2000
(9, 5)	10000	0	0	3000	0	4000	0	3000	0	0	0	0	0
(8, 6)	9000	2000	2000	0	0	0	5000	0	0	0	0	0	0
(11, 6)	11000	0	0	0	0	0	6000	0	5000	0	0	0	0
(3, 7)	8000	0	0	0	1000	2000	0	2000	0	1000	0	1000	1000
(5, 7)	12000	1000	1000	4000	1000	0	0	4000	0	0	0	1000	0
(4, 7)	10000	0	0	1000	0	4000	0	5000	0	0	0	0	0
(6, 8)	10000	0	0	0	0	1000	0	0	6000	1000	1000	0	1000
(10, 8)	8000	0	0	0	0	0	1000	0	1000	1000	0	0	5000
(12, 8)	14000	1000	1000	0	1000	0	3000	0	4000	0	3000	1000	0
(5, 9)	10000	0	0	0	0	0	1000	0	2000	3000	1000	0	3000
(11, 9)	4000	0	0	0	0	0	0	0	0	4000	0	0	0
(12, 9)	11000	0	0	2000	0	3000	0	2000	0	4000	0	0	0
(8,10)	[illegible]	0	0	0	2000	0	0	0	0	0	5000	2000	0
(11,10)	[illegible]	0	0	0	0	0	0	0	0	0	6000	0	4000
(4,11)	[illegible]	0	0	0	0	0	5000	0	4000	3000	5000	6000	3000
(6,11)	[illegible]	[illegible]	3000	1000	1000	0	0	1000	0	0	0	1000	0
(9,11)	[illegible]	[illegible]	[illegible]	0	1000	0	0	0	0	0	0	1000	0
([illegible],11)	[illegible]	[illegible]	[illegible]	1000	3000	1000	0	1000	0	0	0	3000	0
([illegible],12)	[illegible]	[illegible]	0	1000	0	2000	0	1000	0	3000	0	0	7000
([illegible],12)	[illegible]	[illegible]	0	0	0	0	2000	0	3000	0	2000	0	4000

TABLE 1.7

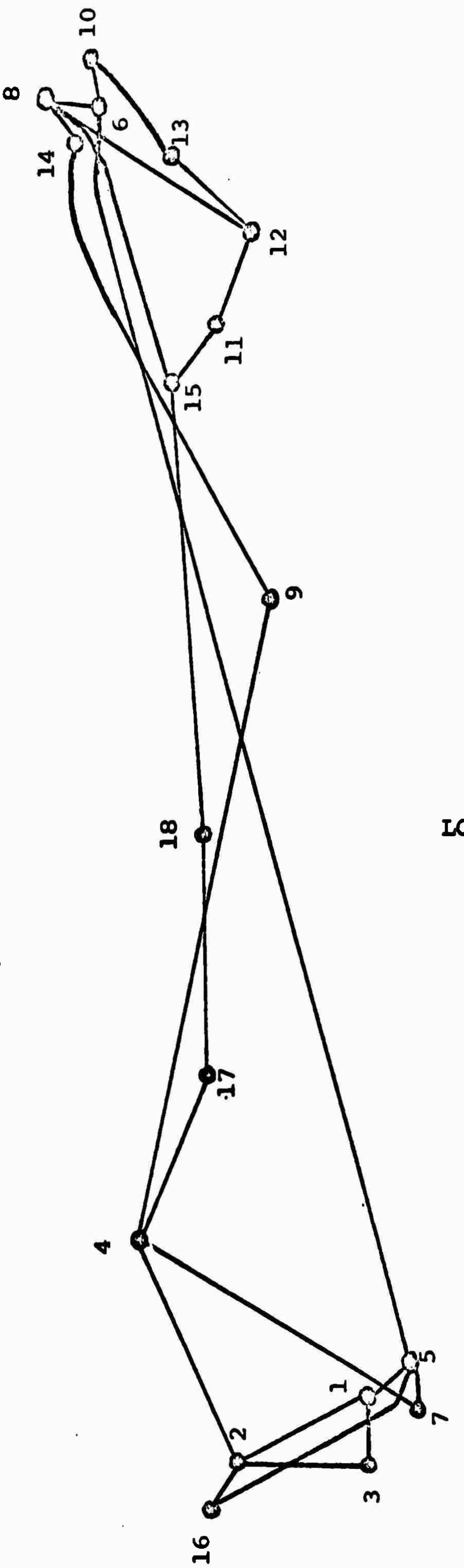
EXAMPLE OF LINK TRAFFIC IN THE OPTIMAL ROUTING

Average No. Bits/Sec/Node = 8120

Average Delay Time = 0.0437

LINK TRAFFIC FROM

LINK	TOTAL LINK TRAFFIC	Node 1	2	3	4	5	6	7	8	9	10	11	12
(2, 1)	2500	1250	0	1250	0	0	0	0	0	0	0	0	0
(3, 1)	10000	3750	2500	0	0	0	1250	0	0	0	1250	1250	0
(4, 1)	13750	8750	0	5000	0	0	0	0	0	0	0	0	0
(1, 2)	3750	0	3750	0	0	0	0	0	0	0	0	0	0
(4, 2)	10000	0	10000	0	0	0	0	0	0	0	0	0	0
(1, 3)	10000	0	0	7500	0	1250	0	1250	0	0	0	0	0
(7, 3)	10000	2500	1250	6250	0	0	0	0	0	0	0	0	0
(2, 4)	11250	0	0	0	1250	1250	1250	1250	1250	1250	1250	1250	1250
(1, 4)	12500	0	0	0	1250	0	2500	0	1250	1250	2500	2500	1250
(7, 4)	10000	0	1250	0	3750	0	1250	0	0	0	1250	2500	0
(11, 4)	31250	7500	7500	3750	7500	1250	0	3750	0	0	0	0	0
(7, 5)	15000	0	0	0	0	7500	0	0	2500	2500	0	0	2500
(9, 5)	13750	0	0	3750	0	6250	0	3750	0	0	0	0	0
(8, 6)	13750	2500	2500	0	0	0	6250	0	0	0	0	2500	0
(11, 6)	15000	0	0	0	0	0	7500	0	5000	0	0	0	2500
(3, 7)	10000	0	0	0	1250	2500	0	2500	1250	1250	0	0	1250
(5, 7)	15000	1250	1250	5000	1250	0	0	5000	0	0	0	1250	0
(4, 7)	10000	0	0	0	0	3750	0	6250	0	0	0	0	0
(6, 8)	13750	0	0	0	0	1250	0	0	6250	1250	1250	0	3750
(10, 8)	8750	0	0	0	0	1250	1250	0	1250	1250	0	0	3750
(12, 8)	18750	1250	1250	0	1250	0	3750	0	6250	0	3750	1250	0
(5, 9)	13750	0	0	0	0	0	1250	0	3750	3750	1250	0	3750
(11, 9)	5000	0	0	0	0	0	0	0	0	5000	0	0	0
(12, 9)	15000	0	0	2500	0	5000	0	2500	0	5000	0	0	0
(8,10)	[illegible]	0	0	0	2500	0	0	0	0	0	6250	0	0
(11,10)	[illegible]	0	0	0	0	0	0	0	0	0	7500	0	2500
(4,11)	[illegible]	0	0	0	0	0	6250	0	3750	3750	6250	7500	3750
(6,11)	[illegible]	3750	3750	1250	1250	0	0	1250	0	0	0	3750	0
(9,11)	[illegible]	[illegible]	1250	0	1250	0	0	0	0	0	0	1250	0
(10,11)	[illegible]	[illegible]	[illegible]	1250	3750	0	0	1250	0	0	0	1250	0
(4,12)	[illegible]	0	0	1250	0	3750	0	1250	0	3750	0	0	8750
(9,12)	[illegible]	0	0	0	0	0	2500	0	5000	0	2500	0	5000



LOW COST 18 NODE NETWORK

THE 18 NODE NETWORK
USED FOR ROUTING
COMPARISON.

FIGURE 1.3

TABLE 1.8

ADJACENCY MATRIX

1-	2	3	5	
2-	1	3	4	16
3-	1	2		
4-	2	7	9	17
5-	1	6	7	16
6-	5	8	10	
7-	4	5		
8-	6	12	14	15
9-	4	14		
10-	6	13		
11-	12	15		
12-	8	11	13	
13-	10	12		
14-	8	9		
15-	8	11	18	
16-	2	5		
17-	4	18		
18-	15	17		

CAPACITY MATRIX

1-	50000	50000	50000	
2-	50000	50000	50000	230400
3-	50000	50000		
4-	50000	50000	50000	50000
5-	50000	100000	230400	50000
6-	100000	230400	230400	
7-	50000	230400		
8-	230400	50000	50000	
9-	50000	50000		
10-	230400	50000		
11-	50000	50000		
12-	50000	50000	50000	
13-	50000	50000		
14-	50000	50000		
15-	50000	50000	50000	
16-	230400	50000		
17-	50000	50000		
18-	50000	50000		

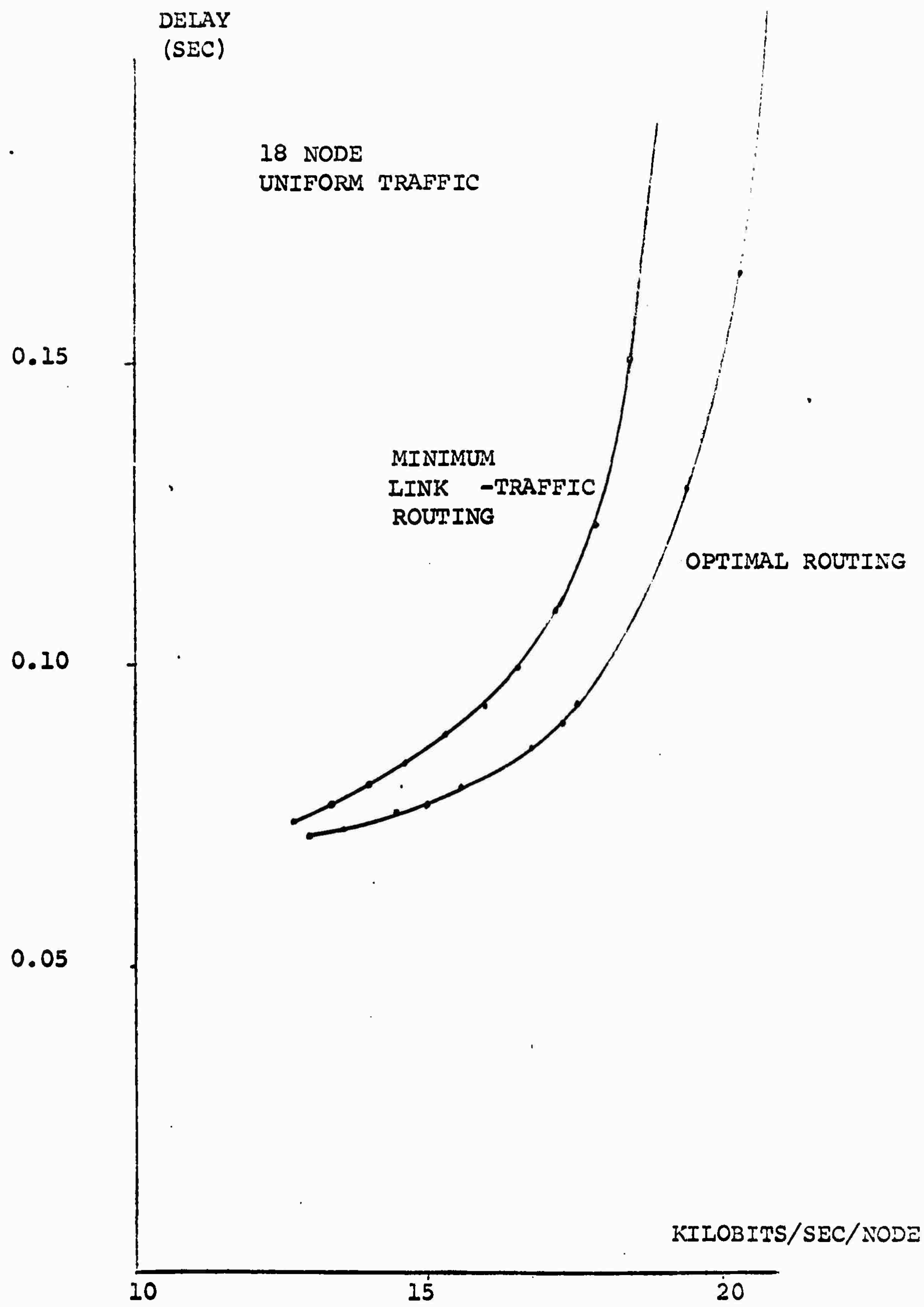

DELAY
(SEC)
18 NODE
UNIFORM TRAFFIC
0.15
MINIMUM
LINK -TRAFFIC
ROUTING
OPTIMAL ROUTING
0.10
0.05
KILOBITS/SEC/NODE
10
15
20

FIGURE 1.4

TABLE 1.9

MINIMUM LINK TRAFFIC ROUTES

Source Node 1

1	2	4			
1	5	6			
1	5	7			
1	2	16			
1	5	6	8		
1	2	4	9		
1	5	6	10		
1	2	4	17		
1	5	6	8	12	
1	5	6	10	13	
1	2	4	9	14	
1	5	6	8	15	
1	2	4	17	18	
1	5	6	8	12	11

Source Node 2

2	16	5			
2	4	7			
2	4	9			
2	4	17			
2	16	5	6		
2	4	9	14		
2	4	17	18		
2	1	5	6	8	
2	1	5	6	10	
2	4	17	18	15	
2	4	17	18	15	11
2	1	5	6	8	12
2	1	5	6	10	13

Source Node 3

3	2	4				
3	1	5				
3	2	16				
3	1	5	6			
3	1	5	7			
3	2	4	9			
3	2	4	17			
3	1	5	6	8		
3	1	5	6	10		
3	2	4	9	14		
3	2	4	17	18		
3	1	5	6	8	12	
3	1	5	6	10	13	
3	2	4	17	18	15	
3	1	5	6	8	12	11

Source Node 4

4	2	1			
4	2	3			
4	7	5			
4	9	14			
4	2	16			
4	17	18			
4	7	5	6		
4	9	14	8		
4	17	18	15		
4	7	5	6	10	
4	17	18	15	11	
4	9	14	8	12	
4	9	14	8	12	13

Source Node 5

5	16	2		
5	1	3		
5	7	4		
5	6	8		
5	6	10		
5	7	4	9	
5	6	8	12	
5	6	10	13	
5	6	8	14	
5	6	8	15	
5	7	4	17	
5	6	8	12	11
5	7	4	17	18

Source Node 6

6	5	1		
6	5	7		
6	8	12		
6	10	13		
6	8	14		
6	8	15		
6	5	16		
6	5	16	2	
6	5	1	3	
6	5	7	4	
6	8	14	9	
6	8	12	11	
6	8	15	18	
6	8	15	18	17

Source Node 7

7	5	1			
7	4	2			
7	5	6			
7	4	9			
7	5	16			
7	4	17			
7	5	1	3		
7	5	6	8		
7	5	6	10		
7	4	9	14		
7	4	17	18		
7	5	6	8	12	
7	5	6	10	13	
7	4	17	18	15	
7	4	17	18	15	11

Source Node 8

8	6	5		
8	14	9		
8	6	10		
8	15	11		
8	12	13		
8	15	18		
8	6	5	1	
8	14	9	4	
8	6	5	7	
8	6	5	16	
8	15	18	17	
8	14	9	4	2
8	6	5	1	3

Source Node 9

9	4	2		
9	4	7		
9	14	8		
9	4	17		
9	4	2	1	
9	4	2	3	
9	4	7	5	
9	14	8	6	
9	14	8	12	
9	14	8	15	
9	4	2	16	
9	4	17	18	
9	14	8	6	10
9	14	8	15	11
9	14	8	12	13

Source Node 10

10	6	5			
10	6	8			
10	13	12			
10	6	5	1		
10	6	5	7		
10	13	12	11		
10	6	8	14		
10	6	8	15		
10	6	5	16		
10	6	5	1	2	
10	6	5	1	3	
10	6	5	7	4	
10	6	8	14	9	
10	6	8	15	18	
10	6	8	15	18	17

Source Node 11

11	12	8				
11	12	13				
11	15	18				
11	12	8	6			
11	12	13	10			
11	12	8	14			
11	15	18	17			
11	15	18	17	4		
11	12	8	6	5		
11	12	8	14	9		
11	12	8	6	5	1	
11	15	18	17	4	2	
11	15	18	17	4	7	
11	12	8	6	5	16	
11	12	8	6	5	1	3

Source Node 12

12	8	6			
12	13	10			
12	8	14			
12	11	15			
12	8	6	5		
12	8	14	9		
12	11	15	18		
12	8	6	5	1	
12	8	14	9	4	
12	8	6	5	7	
12	8	6	5	16	
12	11	15	18	17	
12	8	14	9	4	2
12	8	6	5	1	3

Source Node 13

13	10	6			
13	12	8			
13	12	11			
13	10	6	5		
13	12	8	14		
13	12	11	15		
13	10	6	5	1	
13	10	6	5	7	
13	12	8	14	9	
13	10	6	5	16	
13	12	11	15	18	
13	10	6	5	1	2
13	10	6	5	1	3
13	12	8	14	9	4
13	12	11	15	18	17

Source Node 14

14	9	4		
14	8	6		
14	8	12		
14	8	15		
14	9	4	2	
14	8	6	5	
14	9	4	7	
14	8	6	10	
14	8	15	11	
14	8	12	13	
14	9	4	17	
14	8	15	18	
14	9	4	2	1
14	9	4	2	3
14	9	4	2	16

Source Node 15

15	8	6			
15	11	12			
15	8	14			
15	18	17			
15	18	17	4		
15	8	6	5		
15	8	14	9		
15	8	6	10		
15	11	12	13		
15	8	6	5	1	
15	18	17	4	2	
15	18	17	4	7	
15	18	6	5	16	
15	18	17	4	2	3

Source Node 16

16	2	1			
16	2	3			
16	2	4			
16	5	6			
16	5	7			
16	5	6	8		
16	2	4	9		
16	5	6	10		
16	2	4	17		
16	5	6	8	12	
16	5	6	10	13	
16	2	4	9	14	
16	5	6	8	15	
16	2	4	17	18	
16	5	6	8	12	11

Source Node 17

17	4	2			
17	4	7			
17	4	9			
17	18	15			
17	4	2	1		
17	4	2	3		
17	4	7	5		
17	18	15	8		
17	18	15	11		
17	4	9	14		
17	4	2	16		
17	18	15	8	6	
17	18	15	11	12	
17	18	15	8	6	10
17	18	15	8	12	13

Source Node 18

18	17	4		
18	15	8		
18	15	11		
18	17	4	2	
18	15	8	6	
18	17	4	7	
18	17	4	9	
18	15	11	12	
18	15	8	14	
18	17	4	2	1
18	17	4	2	3
18	17	4	7	5
18	15	8	6	10
18	15	11	12	13
18	17	4	2	16

TABLE 1.10

OPTIMAL ROUTES

Source Node 9

	9	4	2			
	9	4	7			
	9	14	8			
	9	4	17			
	9	4	2	1		
	9	4	2	3		
	9	4	7	5		
	9	14	8	6		
	9	14	8	12		
	9	14	8	15		
	9	4	2	16		
	9	4	17	18		
	9	14	8	6		
	9	14	8	6	10	
*	9	14	8	12	11	
*	9	14	8	6	10	13

TABLE 1.11

TIME DELAY ANALYSIS - MINIMUM LINK TRAFFIC ROUTING

Average No. Bits/Sec/Node	Delay (Sec)
12750	.0745
13387	.0771
14025	.0801
14662	.0836
15300	.0879
15937	.0931
16575	.0999
17212	.1091
17850	.1231
18487	.1510

TABLE 1.12

TIME DELAY ANALYSIS - OPTIMAL ROUTING

Average No. Bits/Sec/Node	Delay (Sec)
12950	.0700
13160	.07157
13600	.0729
13900	.0739
14450	.0755
15000	.0771
15380	.07785
15550	.07927
16850	.08648
17300	.09108
17600	.09387

	[illegible]	1	2	3	4	5	6	7	8	9
(2. 1)	[illegible]	[illegible]	0	0	0	0	0	0	0	
(3. 1)	[illegible]	1000	0	0	0	479	1000	1000	1000	
(5. 1)	[illegible]	[illegible]	0	[illegible]	0	0	0	0	0	
(1. 2)	[illegible]	0	1000	0	1000	0	0	0	0	100
(3. 2)	[illegible]	0	1000	0	1000	521	0	0	0	100
(4. 2)	[illegible]	[illegible]	[illegible]	5000	0	0	0	0	0	
(15. 2)	[illegible]	[illegible]	10000	1521	1000	0	0	0	0	100
(1. 3)	[illegible]	[illegible]	0	[illegible]	0	0	0	0	0	
(2. 3)	[illegible]	[illegible]	0	7521	0	0	0	0	0	
([illegible]. 4)	[illegible]	[illegible]	0	0	4000	0	0	0	0	400
(7. [illegible])	[illegible]	0	0	0	7000	0	0	0	0	200
([illegible]. 4)	[illegible]	[illegible]	2000	[illegible]	2000	1042	0	2000	0	
(17. [illegible])	[illegible]	[illegible]	2000	2000	4000	2000	0	2000	0	200
(1. 5)	[illegible]	0	0	0	0	1479	2000	2000	2000	
(6. 5)	[illegible]	7000	7000	7000	5000	7958	0	7000	0	
(7. 5)	[illegible]	1000	1000	1000	0	5042	2000	0	2000	
(15. 5)	[illegible]	0	0	0	0	2521	2000	2000	2000	
(5. 6)	[illegible]	0	0	0	0	0	7000	0	7000	
([illegible]. 6)	[illegible]	3479	4000	4000	2000	4958	8000	4000	0	
(10. 6)	[illegible]	2521	2000	2000	2000	2000	2000	2000	2000	200
(4. 7)	[illegible]	0	0	0	0	4042	1000	5000	1000	
(5. 7)	[illegible]	0	0	0	6000	0	0	12000	0	100
(6. [illegible])	[illegible]	0	0	0	0	0	0	0	10000	300
(12. 8)	[illegible]	479	1042	1000	1000	2000	2000	1000	2000	200
(14. [illegible])	[illegible]	0	0	0	0	958	2000	0	2000	
(15. [illegible])	[illegible]	2000	[illegible]	2000	0	1000	3000	2000	3000	100
([illegible]. 9)	[illegible]	0	0	0	0	0	0	0	0	900
(14. 9)	[illegible]	1000	1000	1000	1000	42	0	1000	0	800
(6.10)	[illegible]	0	0	0	0	0	0	0	0	
(13.10)	[illegible]	1521	1000	1000	1000	1000	1000	1000	1000	100
(12.11)	[illegible]	0	0	0	0	0	0	0	0	
(15.11)	[illegible]	0	0	0	0	0	0	0	0	
([illegible].12)	[illegible]	0	0	0	0	0	0	0	0	
(11.12)	[illegible]	0	42	0	0	1000	1000	0	1000	100
(1[illegible].12)	7521	0	0	0	0	0	0	0	0	
(1[illegible].13)	[illegible]	0	0	0	0	0	0	0	0	
(12.13)	[illegible]	521	0	0	0	0	0	0	0	
([illegible].1[illegible])	[illegible]	0	0	0	0	0	0	0	0	70
([illegible].1[illegible])	[illegible]	0	0	0	0	0	1000	0	1000	
([illegible].1[illegible])	[illegible]	0	0	0	0	0	0	0	0	
(11.1[illegible])	[illegible]	[illegible]	[illegible]	1000	1000	0	0	1000	0	
(1[illegible].1[illegible])	[illegible]	0	0	0	0	0	2000	0	2000	
(2.1[illegible])	[illegible]	0	0	0	0	1521	1000	1000	1000	
([illegible].1[illegible])	[illegible]	0	[illegible]	521	0	0	0	0	0	
([illegible].1[illegible])	[illegible]	0	0	0	0	0	0	0	0	
(1[illegible].17)	[illegible]	[illegible]	[illegible]	1000	3000	1000	0	1000	0	10
(1[illegible].1[illegible])	[illegible]	0	0	0	2000	0	0	0	0	
(17.1[illegible])	[illegible]	0	0	0	0	0	1000	0	1000	

6	7	8	9	10	11	12	13	14	15	16	17	18
0	0	0	0	0	0	0	0	0	0	0	0	0
1000	1000	1000	0	1000	1000	1000	1000	0	1000	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1000	0	0	0	0	1000	0	1000	1000	1000
0	0	0	1000	0	0	0	0	1000	0	1000	1000	1000
0	0	0	0	0	0	0	0	0	0	5000	0	0
0	0	0	1000	0	0	0	0	1000	0	0	1000	1000
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	4000	0	0	0	0	4000	0	0	4000	4000
0	0	0	2000	0	0	0	0	1042	0	0	2000	2000
0	2000	0	0	0	0	0	0	0	0	2000	2000	1000
0	2000	0	2000	0	0	0	0	1000	0	2000	0	0
2000	2000	2000	0	2000	2000	2000	2000	0	2000	0	0	0
0	7000	0	0	0	0	0	0	0	0	7000	0	0
2000	0	2000	0	2000	1000	2000	2000	0	1000	1000	0	0
2000	2000	2000	0	2000	2000	2000	2000	0	2000	0	0	0
7000	0	7000	0	7000	6000	7000	7000	958	6000	0	0	0
8000	4000	0	0	6000	0	0	3000	0	0	4000	0	0
2000	2000	2000	2000	0	0	0	0	2000	1000	2000	1000	1000
1000	5000	1000	0	1000	0	1000	1000	0	0	0	0	0
0	12000	0	1000	0	0	0	0	42	0	0	1000	1000
0	0	10000	3000	0	6479	8000	0	3958	8000	0	2000	2000
2000	1000	2000	2000	0	0	0	0	2000	0	2000	0	0
2000	0	2000	0	2000	2000	2000	2000	0	2000	0	0	1000
3000	2000	3000	1000	3000	0	0	0	2000	0	1000	0	0
0	0	0	9000	0	0	0	0	7042	0	0	0	0
0	1000	0	8000	0	0	0	0	0	0	1000	1000	0
0	0	0	0	14000	521	0	11000	0	0	0	0	0
1000	1000	1000	1000	3000	0	0	0	1000	0	1000	0	0
0	0	0	0	0	9042	0	0	0	2000	0	2000	2000
0	0	0	0	0	7958	3000	3000	0	0	0	0	0
0	0	0	0	0	5521	11000	0	0	0	0	0	0
1000	0	1000	1000	1000	0	4000	4000	1000	0	1000	0	0
0	0	0	0	0	2521	2000	0	0	1000	0	1000	1000
0	0	0	0	0	1521	1000	12000	0	0	0	0	0
0	0	0	0	2000	0	0	5000	0	0	0	0	0
0	0	0	7000	0	0	0	0	8958	0	0	0	0
1000	0	1000	0	1000	1000	1000	1000	8042	1000	0	0	0
0	0	0	0	0	3958	0	0	0	11000	0	3000	4000
0	1000	0	0	0	0	0	0	0	3000	0	3000	3000
2000	0	2000	0	2000	3000	2000	2000	1000	3000	0	0	0
1000	1000	1000	0	1000	1000	1000	1000	0	1000	8000	0	0
0	0	0	0	0	0	0	0	0	0	9000	0	0
0	0	0	0	0	1000	0	0	0	1000	0	9000	8000
0	1000	0	1000	0	0	0	0	0	0	1000	8000	0
0	0	0	0	0	0	0	0	0	0	0	7000	8000
1000	0	1000	0	1000	2000	1000	1000	0	2000	0	0	9000

EXAMPLE OF BRANCH TRAFFIC IN THE OPTIMAL ROUTING

Average No. Bits/Sec/Node = 12950

Average Delay Time = 0.0700

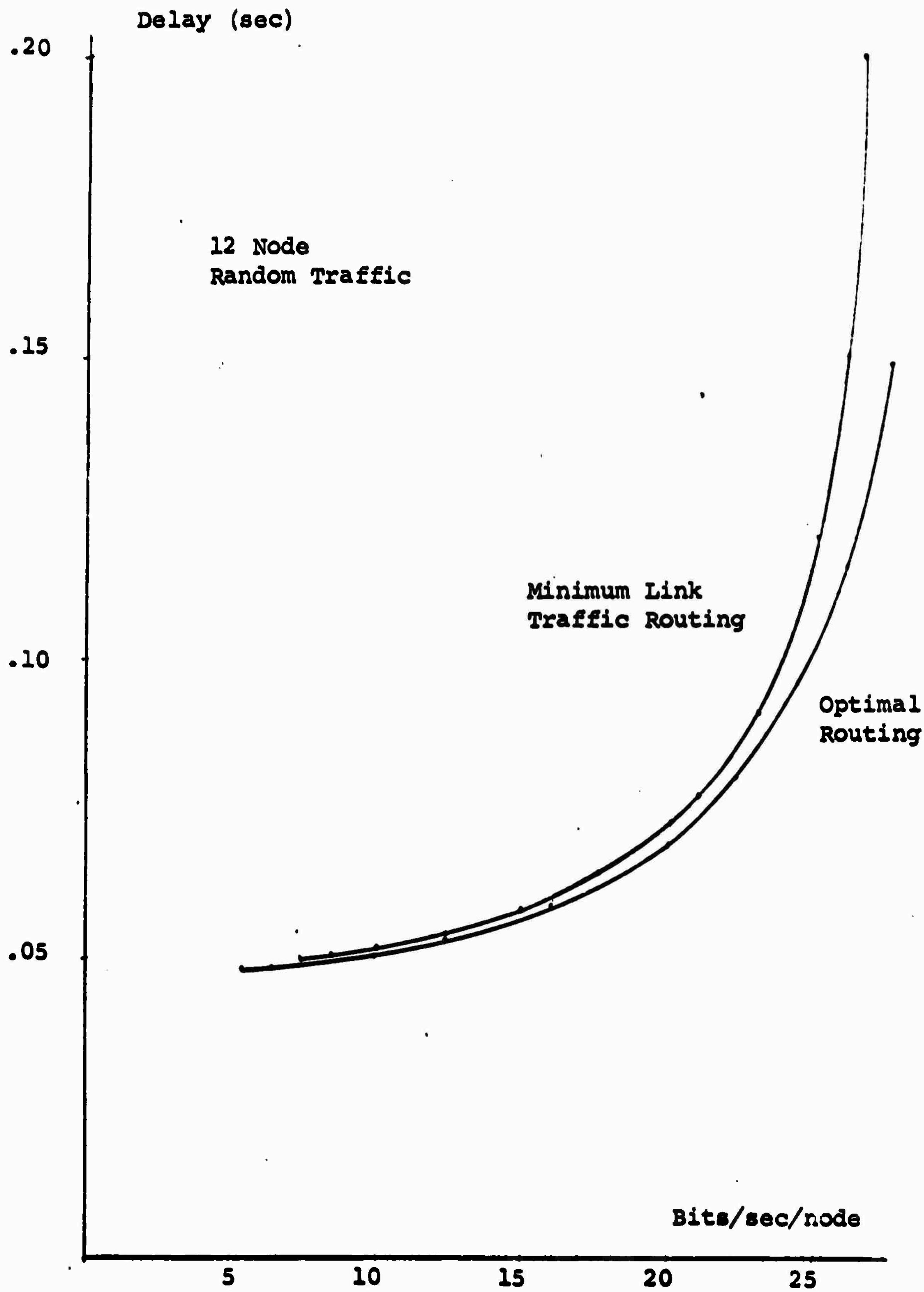

Delay (sec)
.20
.15
.10
.05
12 Node
Random Traffic
Minimum Link
Traffic Routing
Optimal
Routing
Bits/sec/node
5
10
15
20
25

FIGURE 1.5

TABLE 1.14

TIME DELAY ANALYSIS - MINIMUM LINK TRAFFIC ROUTING

(12 nodes, random traffic)

Average No. Bits/Sec/Node	Delay (Sec)
8582	.0502
10601	.0522
11106	.0527
12621	.0546
13630	.0560
15145	.0585
17669	.0640
20193	.0723
21203	.0770
22212	.0830
23222	.0910
24232	.1025
25241	.1207
26251	.1573
26756	.2009
27261	.4343

TABLE 1.15

TIME DELAY ANALYSIS - OPTIMAL ROUTING

(12 nodes, random traffic)

Average No. Bits/Sec/Node	Delay (Sec)
5467	0.0476
6490	0.0484
7031	0.0487
11402	0.0525
15986	0.0591
20031	0.0693
22500	0.0798
24495	0.0962
25084	0.1020
27750	0.1500

II. MINIMUM LINK TRAFFIC ROUTING

The routing procedure is determined by the assumption that for each message a path which contains the fewest number of intermediate nodes from origin to destination is most desirable.

Basic Algorithm

Given a proposed network configuration and its required traffic matrix, routes are determined as follows: For each i ($i = 1, 2, \ldots, N$):

1. With node i as an initial node, use a labelling procedure to generate all paths containing the fewest number of intermediate nodes, to all nodes which have non-zero traffic from node i. Such paths are called feasible paths.

2. If node i has non-zero traffic to node j ($j = 1, 2, \ldots, N$, $j \neq i$) and the feasible paths from i to j contain more than NMAX nodes, (NMAX is a fixed number) the topology is considered infeasible.

3. Nodes are grouped as follows:

   (a) All nodes connected to node i.

(b) All nodes connected to node i by a feasible path with one intermediate node.

(c) All nodes connected to node i by a feasible path with two intermediate nodes.

(d) - - - - - - - - - -

(e) - - - - - - - - - -

(f) All nodes connected to node i by a feasible path with NMAX - 2 intermediate nodes.

Traffic is first routed from node i to any node j which is directly connected to i over link (i,j). Consequently, after this stage, some flows have been assigned to the network. Each node in group (b) is then considered. For any node j in this group, all feasible paths from i to j are examined, and the maximum flow thus far assigned in any link in each such path is found. All paths with the smallest maximum flow are then considered. (See remarks in next paragraph). The path whose total length is minimum is then selected and all traffic originating at i and destined for j is routed over this path. All nodes in group (b) are treated in this manner. The same procedure is then applied to all nodes in group (c), (d), (e) and (f) in that order.

Modifications of Basic Algorithm

It is also possible to divide the traffic from i to j and send it over more than one feasible path but for uniform traffic this is not an important factor. Moreover, we have examined routing strategies for which the selection of the appropriate path from a set of minimum node paths was made by examining a more general function than the minimum of the maximum link flows. The functions tested were computed by examining at every step the already assigned traffic within each link in each path and determining the least cost link capacity required to accommodate this traffic. In one case, link utilization factors were found by computing the ratio of link traffic to link capacity. The maximum link utilization factor in each path was used and the path selected for routing was the one whose maximum utilization factor was minimum. In another case, the residual capacity of each link was calculated as the difference between the required link capacity and the traffic in that link. The path whose smallest residual capacity was maximum was then used. Ties were again resolved by picking the shortest path. In each case, the delays and throughput difference between the basic routing algorithm and the modified algorithm were insignificant.

Sensitivity

Any network design depends crucially on the forecast of the traffic distribution. If this forecast is inaccurate, it can be expected that inefficiencies in performance will occur. In our case, these inefficiencies could be excessive time delay at the desired throughput levels, or equivalently, lower throughputs at saturation. In order to determine the effect of traffic variations on time delay and throughput, several simulation and analysis experiments were conducted.

The basic ARPA configurations were derived with essentially uniform (i.e., equal) traffic between all node pairs. All node pair traffic levels were then increased at the same rate until time delay exceeded 0.2 seconds. The average traffic per node at saturation is defined to be the network's throughput. The following experiment can be performed to examine the effect of widely varying node output rates:

1. A random number Tr(I) bounded by the constants TRL and TRU (i.e., TRL $\leq$ Tr(I) $\leq$ TRU) is selected uniformly at random for node I for I = 1, ..., N. This random number is set equal to the total output of node I.

2. For each node I, N-1 non negative random numbers K(I,1), K(I,2), ... , K(I,N-1) are generated uniformly at random. The traffic from node I to node J is set equal to

$$TR(I)\ K(I,J)/\sum_{J=1}^{n} K(I,J)$$

3. The Minimum Link Traffic Routing Algorithm is applied and the average number of bits/second determined.

4. Steps 1-3 are repeated until a statistically valid sample is obtained.

Steps 1-3 were performed with the twelve and eighteen node networks considered in Chapter 1. Moreover, in our experiments TRL ranged from 1000 to 2000 bits/sec and TRU ranged from 19000 to 38000 bits/sec. The steps were repeated 200 times for the twelve node network and 100 times for the eighteen node network.

Tables 2.1 and 2.2 summarize the data collected. These points are plotted in Figures 2.1 and 2.2 to show the relationship between the sample probabilities observed and the average number of bits/second/node at saturation. For example, point P_1 in Figure 2.1 indicates that of the 200 samples taken, 24 had throughputs of 18,000 bits/second/node.

The effect of inaccurate traffic forecasts for the two networks can be readily investigated. In both the twelve and eighteen node cases, throughputs for uniform traffic distributions were from 10% to 13% higher than the average throughputs for the random samples. In addition, for both networks, more than 75% of the random cases have average throughputs within 17% of the uniform traffic throughput. These numbers demonstrate that the degredation in performance caused by inaccurate traffic forecasts is not severe. Moreover, it can be expected that much of the traffic will not usually deviate significantly from predicted

values. Therefore, throughputs will generally be very close to their nominal values.

TABLE 2.1

12 Node Network

Average Throughput (Bits/Second/Node)	Number of Traffic Patterns
14,000	1
15,000	3
16,000	5
17,000	16
18,000	24
19,000	44
20,000	39
21,000	44
22,000	13
23,000	8
24,000	3

Sample Mean = 20 KBits/Sec/Node

Sample Variance = 400×10^4

Standard Deviation $\doteq$ 2000 Bits/Sec/Node

TABLE 2.2

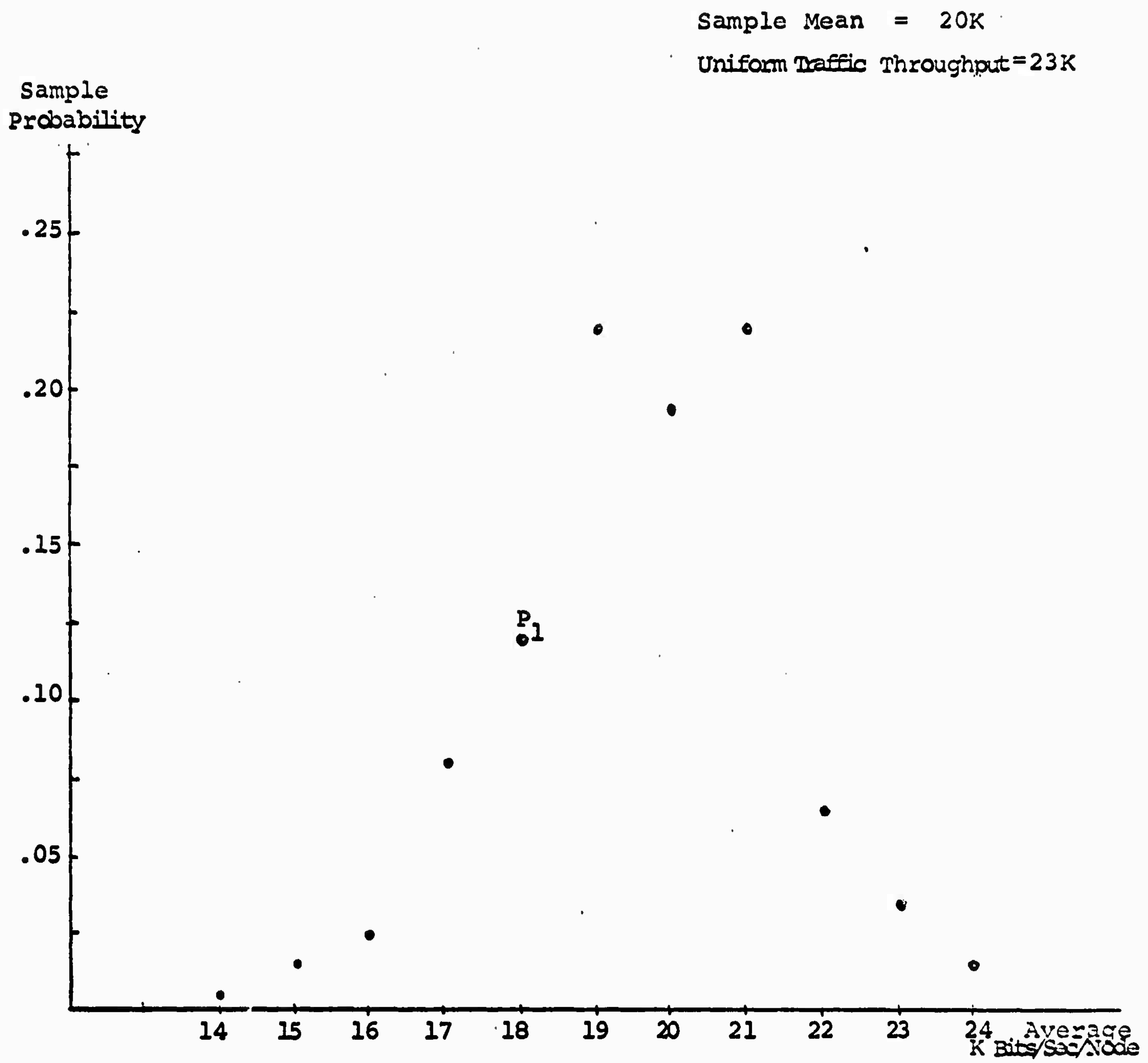
18 Node Network

Average Throughput (Bits/Second/Node)	Number of Traffic Patterns
13,000	1
14,000	5
15,000	16
16,000	19
17,000	33
18,000	18
19,000	5
20,000	3

Sample Mean = 17 KBits/Sec/Node

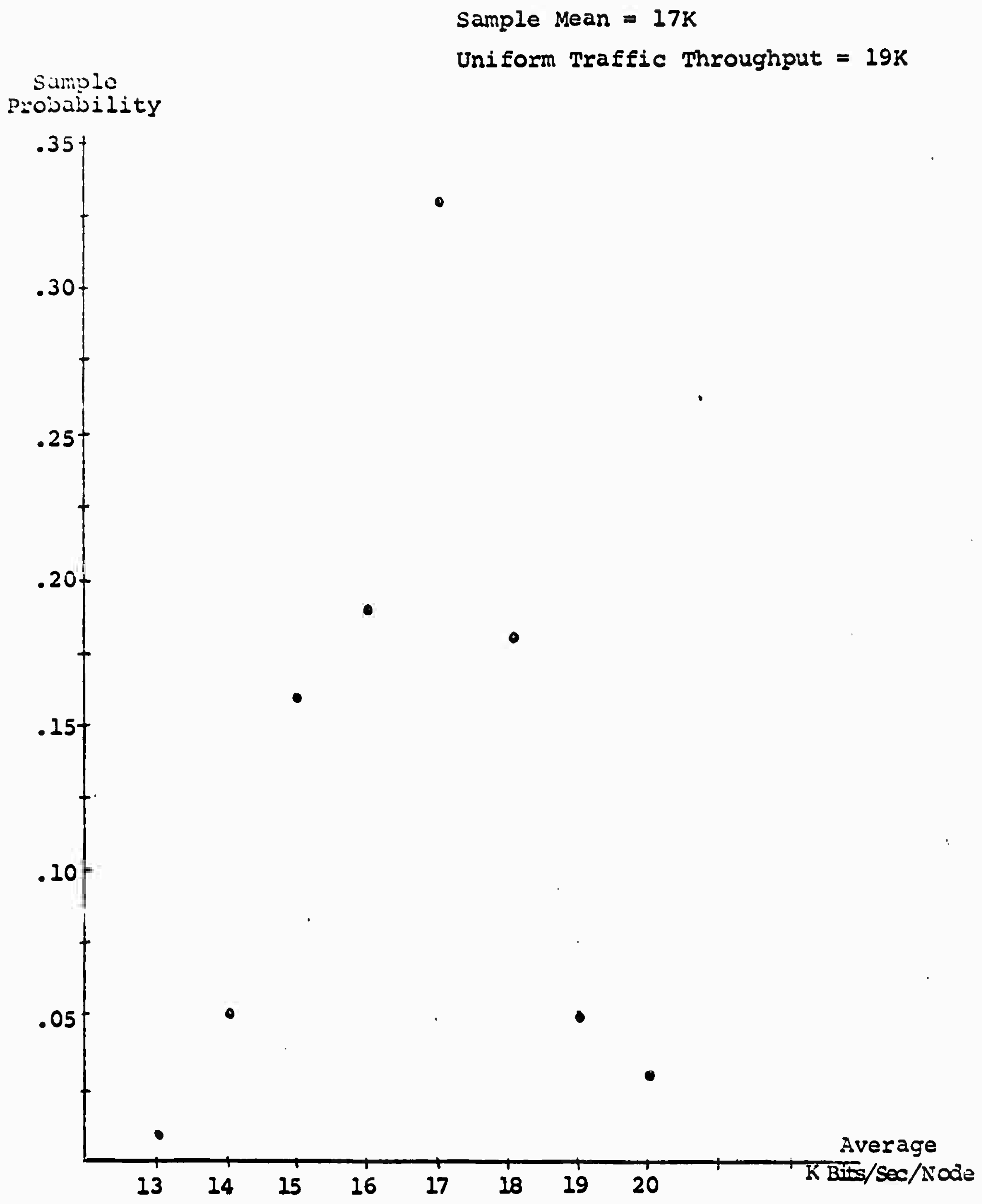
Sample Variance = 221×10^4

Standard Deviation = 1760 Bits/Sec/Node



Empirical Probability Distribution for 12 Node Network

Figure 2.1



Empirical Probability Distribution for 18 Node Network

Figure 2.2

III. COST-THROUGHPUT CHARACTERISTICS OF LARGE NETWORKS

The substantial cost advantages of computer-communications is of particular importance in satisfying the Defense Department's rapidly growing communication requirements. Because this is a new field, much research must be done to uncover the tradeoffs between cost, throughput, and time delay for large networks. Such information is essential for long range planning. Our previous work has exhibited these tradeoffs for the ARPA Computer Network. However, these specific studies were limited to networks with no more than twenty-one nodes - those proposed for inclusion in the network.

In this section, we report the results of our investigation of the cost-throughput characteristics of large networks. The goal of the study is to exhibit these characteristics as a function of the number of nodes in the system. In order to do this, a systematic procedure was established to vary the number of nodes in the networks under consideration and to then find low cost configurations for given levels of traffic. The heart of the procedure is the network design computer program described in References [1] and [2]. In order to establish the basis for our results, we first describe the assumptions and approach.

The factors to be discussed include:

(1) Selection of Node Locations

(2) Cost Factors

(3) Network Model

(4) Network Optimization Program

(5) Selection of Node-to-Node Traffic

Selection of Node Locations

Our previous studies indicated that node locations strongly influence network efficiency. For example, at one traffic level a sixteen node network may be more efficient than the same network with two additional nodes while it may be less efficient at other traffic levels. Consequently, a rigorous basis is required to generate realistic systems with differing numbers of nodes.

Many location algorithms are possible. For example, nodes could be located on the basis of

(1) industrial concentration

(2) distribution of military bases

(3) distribution of universities

(4) population

Since both industry and universities tend to be located at population

centers, distributions produced by these factors are positively correlated. On the other hand, military bases are often located at a distance from population centers, and hence such nodal distributions would have a negative correlation with the others.

The nodal distribution selected was based purely on population. A list of the fifty most populated (1960 census) metropolitan areas was used. These cities, with their latitudes, longitudes and populations are shown in Table 3.1. A required ratio R of population to number of IMP's was assigned to each node, so that if there were P people in a given metropolitan area [P/R] nodes would be assigned to that area, where [x] represents the largest integer no greater than x. Therefore, varying R would vary both the <u>number</u> of nodes in the system, and the <u>location</u> of these nodes.

As an example, if R = 2,000,000, only areas with at least 2,000,000 people would be assigned an Interface Message Processor. Since the New York area has a population of 10,602,382 it would have five IMP's. The Los Angeles area would have three IMP's, the Chicago area three IMP's, and so on. (As a conservative figure, distances between IMP's in the same metropolitan area were taken to be twenty miles). The overall system would then contain nine distinct metropolitan areas with a total of eighteen IMP's. Table 3.2 indicates these relationships as a function of R.

TABLE 3.1

METROPOLITAN AREA	LATITUDE		LONGITUDE		POPULATION
	Degrees	Minutes	Degrees	Minutes	
New York	40	40	73	53	10602382
Los Angeles	34	0	118	15	6668975
Chicago	41	49	87	37	6171517
Philadelphia	40	0	75	13	4301283
Detroit	42	22	83	10	3743447
San Francisco	37	45	122	26	2725841
Boston	42	15	71	7	2566732
Pittsburgh	40	26	80	1	2392086
St. Louis	38	39	90	15	2046477
Washington, D. C.	38	50	77	0	1967682
Cleveland	41	30	81	42	1786740
Baltimore	39	20	76	38	1707462
Newark	40	44	74	10	1682882
Minneapolis	44	58	93	15	1474149
Buffalo	42	54	78	51	1301604
Houston	29	46	95	21	1236704
Milwaukee	43	10	87	56	1184806
Paterson	40	55	74	10	1183514
Seattle	47	36	122	20	1098741
Dallas	32	45	90	48	1071003

METROPOLITAN AREA	LATITUDE Degrees	LATITUDE Minutes	LONGITUDE Degrees	LONGITUDE Minutes	POPULATION
Cincinatti	39	8	84	30	1067669
Kansas	39	5	94	35	1034150
Atlanta	33	45	84	23	1010577
San Diego	32	43	117	10	1000856
Denver	39	44	104	59	925569
Miami	25	45	80	11	921625
New Orleans	30	0	90	5	861299
Portland	45	31	122	40	818776
Providence	41	50	71	23	810145
San Bernardino	34	7	117	19	800865
Tampa	27	58	82	25	759790
Louisville	38	15	85	45	718685
Indianapolis	39	45	86	8	690162
Dayton	39	45	84	15	689339
San Antonio	29	25	98	30	682481
Columbus	40	0	83	0	680183
Phoenix	33	30	112	0	657688
Albany	42	40	73	50	652205
San Jose	37	20	121	54	638054
Birmingham	33	31	86	49	629248
Memphis	35	7	90	3	619722

METROPOLITAN AREA	LATITUDE Degrees	Minutes	LONGITUDE Degrees	Minutes	POPULATION
Jersey City	40	43	74	5	607250
Rochester	43	15	77	35	582777
Gary	41	35	87	21	571799
Syracuse	43	5	76	10	562362
Fort Worth	32	45	97	20	557864
Norfolk	36	55	76	15	541494
Hartford	41	45	72	40	522735
Akron	41	5	81	30	508788
Oklahoma City	35	27	97	32	508581

TABLE 3.2

No. of IMPS (N)	P= Population/IMP	No. of Cities Used
0	over 10602382	0
1	10602382	1
2	6568975	2
3	6171517	3
4	5301191	3
5	4301283	4
6	3743447	5
7	3534127	5
8	3334487	5
9	3085758	5
10	2725841	6
11	2650595	6
12	2566732	7
13	2392086	8
14	2222992	8
15	2150641	8
16	2120476	8
17	2057172	8
18	2046477	9
19	1967682	10
20	1871723	10
21	1786740	11
22	1767064	11
23	1707462	12
24	1682882	13
25	1667244	13
26	1542879	13
27	1514626	13
28	1474149	14
29	1433761	14
30	1362920	14
31	1333795	14
32	1325298	14
33	1301604	15
34	1283365	15
35	1247816	15
36	1236704	16
37	1234303	16
38	1196043	16
39	1184806	17
40	1183514	18
41	1178042	18

TABLE 3.2 (cont'd)

No. of IMPs (N)	R = Population/IMP	No. of Cities Used
42	1111496	18
43	1098741	19
44	1075321	19
45	1071003	20
46	1067669	21
47	1060238	21
48	1034150	22
49	1028586	22
50	1023238	22
51	1010577	23
52	1000856	24
53	983841	24
54	963853	24
55	952711	24
56	935862	24
57	925569	25
58	921625	26
59	908614	26
60	893370	26
61	883532	26
62	881645	26
63	861299	27
64	860257	27
65	855577	27
66	853731	27
67	841441	27
68	833622	27
69	818776	28
70	815568	28
71	810145	29
72	800865	30
73	797362	30
74	771440	30
75	759790	31
76	757313	31
77	748689	31
78	740997	31
79	737074	31
80	718685	32
81	716880	32
82	706825	32
83	690162	33
84	689339	34
85	685724	34
86	682481	35

TABLE 3.2 (cont'd)

No. of IMPs (N)	R = Population/IMP	No. of Cities Used
87	682159	35
88	681460	35
89	680183	36
90	666897	36
91	662649	36
92	657688	37
93	655894	37
94	652205	38
95	650802	38
96	641683	38
97	638054	39
98	629248	40
99	623908	40
100	623670	40

Cost Factors

Cost factors used are those currently applicable to the present ARPA Network. These factors apply to both nodes and links and vary with the capacities of these elements. The factors used are given in Tables 3.3 and 3.4.

TABLE 3.3

LINE COSTS

Capacity	Fixed Cost/Month	Cost Per Mile/Month
10,400 bps	$ 650.00	$ 0.40
19,200 bps	$ 850.00	$ 2.50
50,000 bps	$ 850.00	$ 5.00
230,400 bps	$ 1300.00	$ 30.00

All lines fully duplex

TABLE 3.4

NODE COSTS

Description	Rental Cost/Year	Maintenance/Cost/Year
Standard 516 IMP with up to 6 external fully duplex lines.	$ 25,700	$ 7,600
Economy 316 IMP with up to 3 external fully duplex lines. Processing rate is 3/4 that of 516 IMP.	$ 12,600	$ 5,000

Network Model

The basic network model is described in detail in References [1] and [2]. To complement this description, we point out several important characteristics in the model.

(1) The equation for modeling time delay is given in Section 1 on Optimal Routing.

(2) Minimum Link Traffic Routing, as described in Section 2 , is used.

(3) Acceptable time delay is 0.5 seconds for short messages.

(4) 85% of all messages are short.

(5) Except in the initial experiments on traffic patterns, all acceptable network configurations must be "two connected." That is, at least two nodes and/or links must fail before all paths between any pair of nodes are broken.

Network Optimization Program

The network optimisation program is a more sophisticated version of the one described in References [1] and [2]. The program is given a "starting" network. It then searches for modifications of this network which reduce the cost per bit of transmitted information while continuing to satisfy all constraints. Network modifications consist of additions or deletions of links either one or more at a time. Each time a modification is examined the routing algorithm is reapplied to determine the average delay of the new network.

Because of the high frequency of use of the routing algorithm, special subroutines are designed to minimize the computation time at each step. The basic algorithm operates by assigning numbers, called "labels", to each node. From these labels, the optimum paths are calculated for the overall network. The special subroutines operate by examining these labels before a change in the network structure is made and calculating the effects of the change without recomputing all of the labels. These subroutines usually reduce computation time by a factor of ten when compared to a straightforward application of the basic routing algorithm.

The actual network optimization is based on a "regional decomposition" principle. The system is divided into regions. Nodes are then uniquely assigned to each region. These nodes are classified as either central nodes or local nodes. There may be any number of regions, and the choice of local and central nodes is made by the designer. The distinction between nodes stems from restrictions on allowable connections.

(1) Within a given region any connection is possible.

(2) Connections between regions are only allowed between central nodes.

(3) Any connection between central nodes is possible.

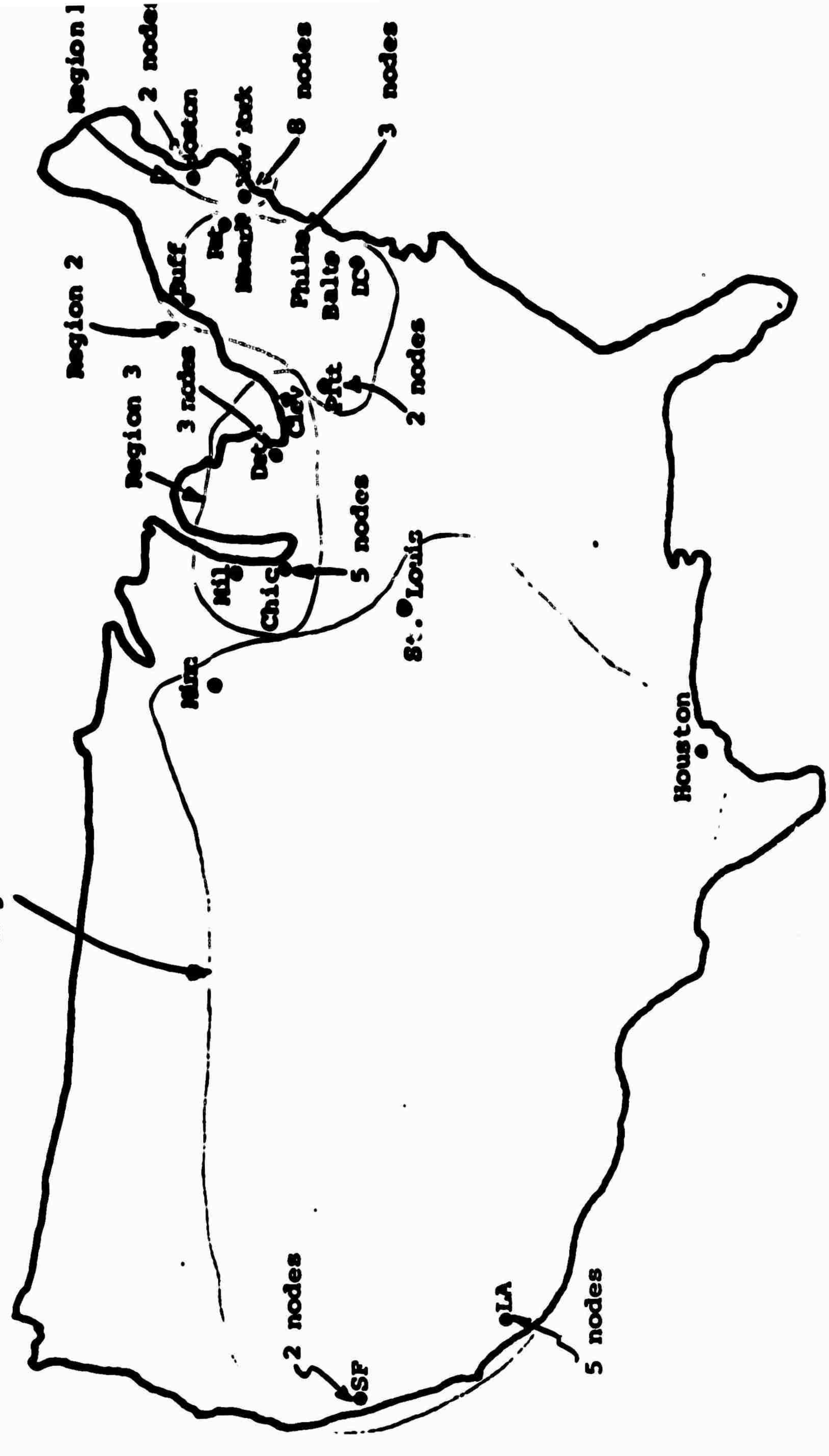
Therefore, a flow from a local node in Region I to a local node in Region J must be routed first to a central node in Region I, then through a "global" network composed of central nodes to a central node in Region J and finally to the local destination node in Region J. Thus, in general a "heirarchal" network is used. If desired structural constraints can be eliminated by declaring every node to be a central node. In this case, there are $N(N-1)/2$ possible links where N is the number of nodes in the network. If N is large, the computational time required for optimization may be prohibitive, and therefore decomposition

is essential. For the sizes of the networks being considered, the decomposition approach produces computation time savings ranging from a factor of ten to factors of more than 400. A typical example of a regional decomposition is shown in Figure 3.1.

Selection of Node-to-Node Traffic

A fundamental problem in all network design is the estimation of the traffic the network must accommodate. For some problems accurate estimates of user requirements may be known. Unfortunately, the field of computer-communications is so new that complete studies are not yet available to predict the flow requirements in general networks of the type being considered here. In fact, a number of basic questions about the nature of these flows are yet to be resolved. For example, it is reasonable to assume that the flow out of a node will be proportional to the population assigned to that node. However, will the flow between two nodes be affected by the distance between these nodes? If so, how will the cost-throughput characteristics of the network be affected?

In order to investigate the effect of different traffic distributions on network economy, a sequence of experiments were conducted in which traffic patterns were varied and low cost networks for these patterns generated. These experiments are described



Example of Regional Decomposition

FIGURE 3.1

as follows. The traffic out of each node in city C_i with population P_i is equal to $KP_i/[P_i/R]$ where R is the required population per IMP, and K is a constant which determines the "traffic level." The traffic from each node in this city to any node in city C_j is equal to

$$K(P_i/[P_i/R]) \frac{(P_j/[P_j/R])d_{i,k}^{\alpha}}{\sum P_k/[P_k/R]d_{i,k}^{\alpha}}$$

where $d_{i,j}$ is the distance between C_i and C_j for $i \neq j$, $d_{i,i} = 20$ miles, and α is a non-negative constant. If $\alpha = 0$, traffic between cities is independent of distance while if $\alpha = 1$, traffic follows the well known "gravity law."

For a fixed number N of nodes and fixed α , K is varied. Each value of K gives a specified distribution of traffic for which a low cost network can be found. For each K a point on curves of cost versus bits/sec/node and cost versus cost per megabit of transmitted information is thus determined. By varying K, a number of values of these parameters are found.

The above experiment was applied for $N = 40$ and $\alpha = 0.0$, 0.5 and 1.0. Typical traffic matrices for $\alpha = 0$ and $\alpha = 1$ are shown in Tables 2.5(a) and (b) below. In these tables, the traffic from one IMP in each city to one IMP in each other city is shown. For the

forty node network, the distribution of cities and IMP's is as follows:

	Metropolitan Area	Number of IMP's
(1)	New York	8
(2)	Los Angeles	5
(3)	Chicago	5
(4)	Philadelphia	3
(5)	Detroit	3
(6)	San Francisco	2
(7)	Boston	2
(8)	Pittsburgh	2
(9)	St. Louis	1
(10)	Washington, D. C.	1
(11)	Cleveland	1
(12)	Baltimore	1
(13)	Newark	1
(14)	Minneapolis	1
(15)	Buffalo	1
(16)	Houston	1
(17)	Milwaukee	1
(18)	Paterson	1

The above IMP distribution list can be used as a guide to interpret the entries in Tables 3.5(a) and (b). For example, each of the eight IMP's in New York generate the traffic listed under the New York entry. From each such IMP, the traffic to each IMP in the metropolitan area numbered i is equal to the i^{th} entry listed under New York. Thus, the traffic from each of the eight IMP's in New York to each of the 3 IMP's in Detroit is equal to 1238 bits/sec when $\alpha = 0$.

The experiments were run before exact costs for hardware were available and hence preliminary estimates of the costs and constraints on the IMP's were used. Each "global" network (i.e., the network connecting the central nodes) was required to be two connected, but the regional networks were only required to be one connected. That is, in these networks, the failure of a single node or line could disconnect a local node from the remainder of the system. In later studies, this requirement was changed to two connectivity because of preliminary statistics that showed that single line failures occur relatively frequently. Finally, the data set for the 10.4 KB line was priced somewhat lower in the traffic studies than in later designs. Hence, the costs in the traffic studies for the forty node networks that are given in Table 3.6 and displayed in Figures 3.2 and 3.3 are not directly compatable with the costs given later in the report.

TABLE 3.5(a)

TRAFFIC DISTRIBUTION, $\alpha = 0$

1. New York (each IMP)

(1)	131	(2)	132	(3)	122	(4)	142	(5)	123	(6)	135
(7)	127	(8)	118	(9)	203	(10)	195	(11)	177	(12)	169
(13)	167	(14)	146	(15)	129	(16)	122	(17)	175	(18)	117

2. Los Angeles (each IMP)

(1)	132	(2)	133	(3)	123	(4)	143	(5)	124	(6)	136
(7)	128	(8)	119	(9)	204	(10)	196	(11)	178	(12)	170
(13)	168	(14)	147	(15)	130	(16)	123	(17)	118	(18)	118

3. Chicago (each IMP)

(1)	122	(2)	123	(3)	113	(4)	132	(5)	115	(6)	125
(7)	118	(8)	103	(9)	188	(10)	164	(11)	164	(12)	157
(13)	115	(14)	136	(15)	120	(16)	114	(17)	109	(18)	109

4. Philadelphia (each IMP)

(1)	123	(2)	124	(3)	115	(4)	151	(5)	133	(6)	127
(7)	119	(8)	111	(9)	190	(10)	183	(11)	166	(12)	159
(13)	157	(14)	137	(15)	121	(16)	115	(17)	110	(18)	110

TABLE 3.5(a) (Cont'd)

5. Detroit (each IMP)

(1)	123	(2)	124	(3)	151	(4)	133	(5)	116	(6)	127
(7)	119	(8)	111	(9)	190	(10)	183	(11)	166	(12)	159
(13)	157	(14)	137	(15)	121	(16)	115	(17)	110	(18)	110

6. San Francisco (each IMP)

(1)	135	(2)	136	(3)	126	(4)	146	(5)	127	(6)	139
(7)	131	(8)	122	(9)	209	(10)	201	(11)	182	(12)	174
(13)	171	(14)	150	(15)	132	(16)	126	(17)	121	(18)	120

7. Boston (each IMP)

(1)	127	(2)	128	(3)	118	(4)	137	(5)	119	(6)	130
(7)	123	(8)	114	(9)	196	(10)	188	(11)	171	(12)	164
(13)	161	(14)	141	(15)	125	(16)	118	(17)	137	(18)	113

8. Pittsburgh (each IMP)

(1)	118	(2)	119	(3)	110	(4)	128	(5)	111	(6)	128
(7)	114	(8)	106	(9)	182	(10)	175	(11)	159	(12)	152
(13)	150	(14)	131	(15)	116	(16)	110	(17)	105	(18)	105

9. St. Louis

(1)	205	(2)	207	(3)	191	(4)	222	(5)	193	(6)	211
(7)	199	(8)	185	(9)	0	(10)	305	(11)	277	(12)	265
(13)	261	(14)	229	(15)	202	(16)	192	(17)	184	(18)	183

TABLE 3.5(a) (Cont'd)

10. Washington, D. C.

(1)	197	(2)	198	(3)	184	(4)	213	(5)	186	(6)	203
(7)	191	(8)	178	(9)	305	(10)	0	(11)	266	(12)	254
(13)	251	(14)	219	(15)	194	(16)	184	(17)	176	(18)	176

11. Cleveland

(1)	178	(2)	180	(3)	166	(4)	193	(5)	168	(6)	183
(7)	173	(8)	161	(9)	276	(10)	265	(11)	0	(12)	230
(13)	227	(14)	198	(15)	175	(16)	166	(17)	159	(18)	159

12. Baltimore

(1)	170	(2)	171	(3)	158	(4)	184	(5)	160	(6)	175
(7)	165	(8)	154	(9)	263	(10)	253	(11)	230	(12)	0
(13)	216	(14)	189	(15)	167	(16)	159	(17)	152	(18)	152

13. Newark

(1)	168	(2)	169	(3)	156	(4)	181	(5)	158	(6)	172
(7)	162	(8)	151	(9)	259	(10)	249	(11)	226	(12)	216
(13)	0	(14)	187	(15)	165	(16)	156	(17)	150	(18)	150

14. Minneapolis

(1)	146	(2)	147	(3)	136	(4)	158	(5)	138	(6)	150
(7)	142	(8)	132	(9)	226	(10)	217	(11)	197	(12)	189
(13)	186	(14)	0	(15)	144	(16)	136	(17)	131	(18)	131

TABLE 3.5(a) (Cont'd)

15. Buffalo

(1)	129	(2)	129	(3)	120	(4)	139	(5)	121	(6)	132
(7)	125	(8)	116	(9)	199	(10)	191	(11)	174	(12)	166
(13)	163	(14)	143	(15)	0	(16)	120	(17)	115	(18)	115

16. Houston

(1)	122	(2)	123	(3)	114	(4)	132	(5)	115	(6)	126
(7)	118	(8)	110	(9)	189	(10)	181	(11)	165	(12,	157
(13)	155	(14)	136	(15)	120	(16)	0	(17)	109	(18)	109

17. Milwaukee

(1)	117	(2)	118	(3)	109	(4)	126	(5)	110	(6)	120
(7)	113	(8)	105	(9)	181	(10)	174	(11)	158	(12)	151
(13)	148	(14)	130	(15)	115	(16)	109	(17)	0	(18)	104

18. Paterson

(1)	117	(2)	117	(3)	109	(4)	126	(5)	110	(6)	120
(7)	113	(8)	105	(9)	180	(10)	173	(11)	157	(12)	150
(13)	148	(14)	130	(15)	115	(16)	109	(17)	104	(18)	0

TABLE 3.5(b)

TRAFFIC DISTRIBUTION, $\alpha = 1$

1. New York (each IMP)

(1)	220	(2)	1	(3)	6	(4)	18	(5)	13	(6)	1
(7)	7	(8)	49	(9)	8	(10)	40	(11)	29	(12)	33
(13)	16	(14)	4	(15)	38	(16)	3	(17)	6	(18)	11

2. Los Angeles (each IMP)

(1)	3	(2)	456	(3)	3	(4)	3	(5)	3	(6)	26
(7)	2	(8)	3	(9)	7	(10)	4	(11)	4	(12)	4
(13)	3	(14)	5	(15)	3	(16)	5	(17)	3	(18)	2

3. Chicago (each IMP)

(1)	11	(2)	3	(3)	339	(4)	9	(5)	22	(6)	3
(7)	6	(8)	12	(9)	46	(10)	14	(11)	23	(12)	12
(13)	9	(14)	19	(15)	11	(16)	8	(17)	91	(18)	6

4. Philadelphia (each IMP)

(1)	37	(2)	3	(3)	10	(4)	523	(5)	16	(6)	3
(7)	30	(8)	25	(9)	14	(10)	104	(11)	28	(12)	119
(13)	149	(14)	8	(15)	32	(16)	6	(17)	9	(18)	99

TABLE 3.5(b) (Cont'd)

5. Detroit (each IMP)

(1)	32	(2)	4	(3)	30	(4)	19	(5)	474	(6)	3
(7)	11	(8)	37	(9)	29	(10)	32	(11)	122	(12)	27
(13)	20	(14)	15	(15)	32	(16)	8	(17)	26	(18)	14

6. San Francisco (each IMP)

(1)	8	(2)	75	(3)	10	(4)	8	(5)	8	(6)	1348
(7)	7	(8)	8	(9)	18	(10)	12	(11)	12	(12)	10
(13)	9	(14)	14	(15)	8	(16)	12	(17)	9	(18)	6

7. Boston (each IMP)

(1)	32	(2)	5	(3)	14	(4)	62	(5)	19	(6)	5
(7)	857	(8)	25	(9)	20	(10)	59	(11)	32	(12)	55
(13)	99	(14)	12	(15)	32	(16)	9	(17)	13	(18)	70

8. Pittsburgh (each IMP)

(1)	101	(2)	3	(3)	14	(4)	26	(5)	31	(6)	2
(7)	12	(8)	366	(9)	17	(10)	53	(11)	84	(12)	43
(13)	25	(14)	9	(15)	54	(16)	6	(17)	12	(18)	17

9. St. Louis

(1)	62	(2)	25	(3)	192	(4)	51	(5)	89	(6)	22
(7)	36	(8)	62	(9)	0	(10)	80	(11)	110	(12)	67
(13)	56	(14)	147	(15)	59	(16)	82	(17)	161	(18)	39

TABLE 3.5(b) (Cont'd)

10. Washington, D. C.

(1)	116	(2)	6	(3)	22	(4)	146	(5)	37	(6)	6
(7)	40	(8)	74	(9)	31	(10)	0	(11)	70	(12)	670
(13)	107	(14)	17	(15)	75	(16)	12	(17)	20	(18)	74

11. Cleveland

(1)	105	(2)	8	(3)	47	(4)	50	(5)	180	(6)	7
(7)	27	(8)	148	(9)	53	(10)	89	(11)	0	(12)	74
(13)	51	(14)	28	(15)	99	(16)	17	(17)	42	(18)	36

12. Baltimore

(1)	88	(2)	5	(3)	18	(4)	156	(5)	29	(6)	4
(7)	35	(8)	56	(9)	24	(10)	627	(11)	55	(12)	0
(13)	103	(14)	14	(15)	62	(16)	10	(17)	16	(18)	71

13. Newark

(1)	49	(2)	5	(3)	16	(4)	213	(5)	24	(6)	49
(7)	69	(8)	35	(9)	22	(10)	109	(11)	41	(12)	112
(13)	0	(14)	13	(15)	46	(16)	9	(17)	14	(18)	723

14. Minneapolis

(1)	46	(2)	26	(3)	104	(4)	40	(5)	62	(6)	23
(7)	29	(8)	45	(9)	194	(10)	60	(11)	77	(12)	51
(13)	44	(14)	0	(15)	46	(16)	57	(17)	111	(18)	31

15. Buffalo

(1)	118	(2)	4	(3)	20	(4)	49	(5)	41	(6)	4
(7)	23	(8)	81	(9)	24	(10)	81	(11)	84	(12)	72
(13)	48	(14)	14	(15)	0	(16)	9	(17)	18	(18)	34

16. Houston

(1)	42	(2)	33	(3)	62	(4)	39	(5)	48	(6)	28
(7)	29	(8)	40	(9)	147	(10)	59	(11)	65	(12)	50
(13)	43	(14)	7	(15)	40	(16)	0	(17)	57	(18)	30

17. Milwaukee

(1)	23	(2)	7	(3)	197	(4)	18	(5)	42	(6)	6
(7)	12	(8)	23	(9)	83	(10)	28	(11)	45	(12)	23
(13)	19	(14)	43	(15)	23	(16)	16	(17)	0	(18)	13

18. Paterson

(1)	31	(2)	3	(3)	10	(4)	128	(5)	15	(6)	3
(7)	44	(8)	22	(9)	14	(10)	68	(11)	26	(12)	69
(13)	65	(14)	8	(15)	29	(16)	6	(17)	9	(18)	0

However, to avoid the extra manpower and computer time needed to repeat the studies with the higher costs, the traffic experiments were not rerun since it is felt that the results are representative.

Table 3.6 indicates the costs and throughputs generated by the procedure indicated above. The results tend to indicate that for given throughputs, slightly lower cost designs can be obtained for greater values of α (i.e., for traffic patterns with which favor flows between nodes close together). These costs and throughputs are graphed in Figures 3.2 and 3 .3. However, the cost differentials between traffic patterns with $\alpha = 1$ (the gravity law) and $\alpha = 0$ (no distance bias) do not appear to be significant. Therefore, for latter studies traffic patterns without distance bias were used exclusively. Thus, the flow from a node in city C_i with population P_i to a node in city C_j with population P_j was assumed to be

$$K(P_i/[P_i/R] \frac{(P_j/[P_j/R])}{\sum P_k/[P_k/R]}$$

for $i \neq j$. The flow from a node in city C_i to another node in the same city is

$$\frac{KP_i^2/[P_i/R]^2}{\sum P_k/[P_k/R]}$$

Naturally, there is zero flow from any node to itself.

TABLE 3.6

α	Yearly Cost (M$)	Yearly Cost/Node (K$)	Total K Bits/Sec of Data	K Bits/Sec/Node	Cost/Megabit of Data (24 hours/day operation)
0.0	$1.64 M	$41 K	172	4	30
0.0	$1.68	$42	219	5	25
0.0	$1.80	$45	290	7	20
0.0	$1.84	$46	323	8	18
0.0	$1.96	$49	538	13	12
0.0	$2.00	$50	944	24	7
0.0	$2.16	$54	924	23	8
0.0	$2.16	$54	1010	25	6
0.0	$2.20	$55	1028	26	7
0.5	$1.70	$45	301	8	19
0.5	$1.88	$47	379	9	16
0.5	$2.08	$52	877	22	8
0.5	$2.24	$56	1062	27	7
1.0	$1.68	$42	282	7	19
1.0	$1.72	$43	255	6	21
1.0	$1.80	$45	331	8	18
1.0	$2.00	$50	495	12	14
1.0	$2.08	$52	763	19	9
1.0	$2.20	$55	1146	29	5

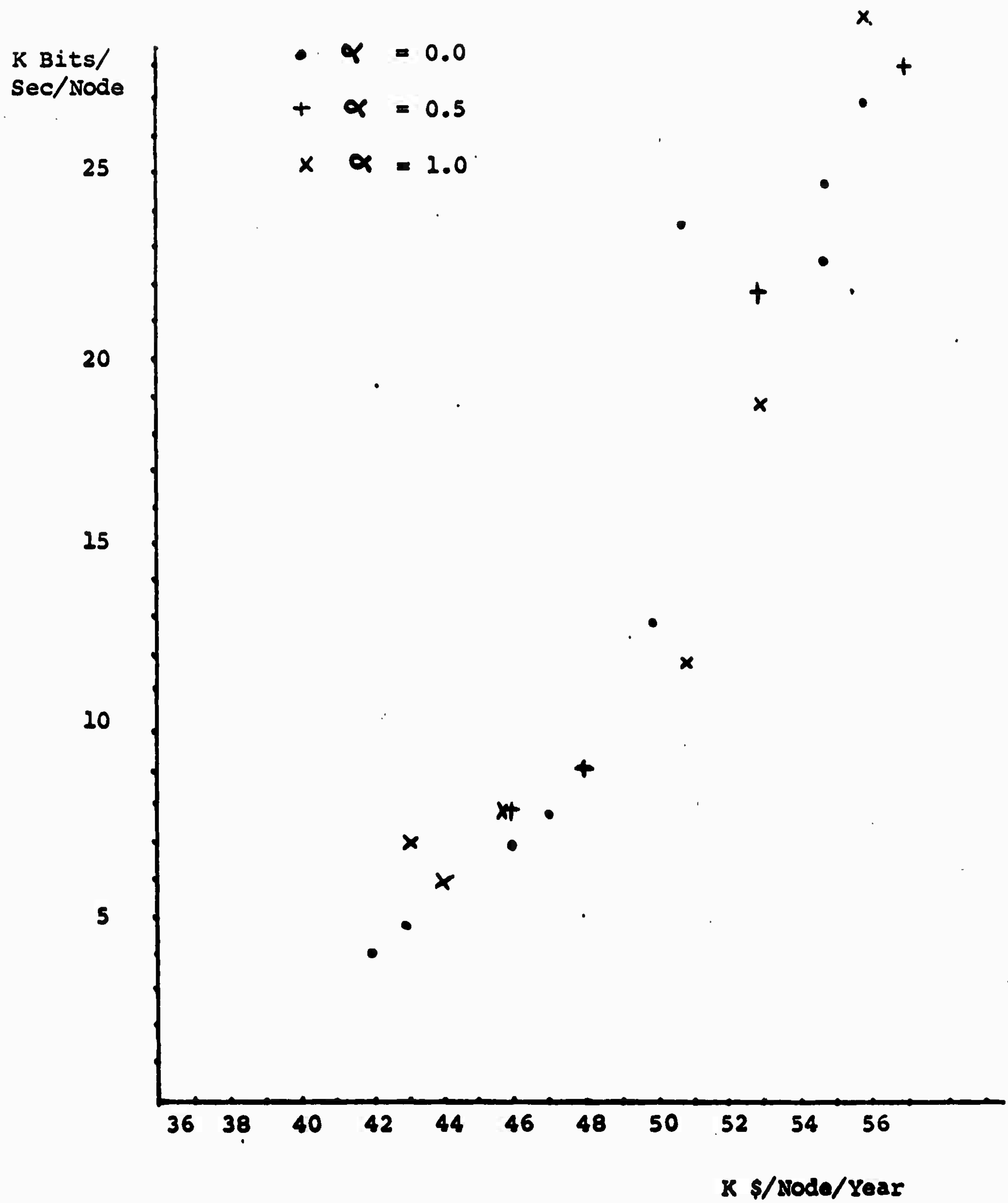
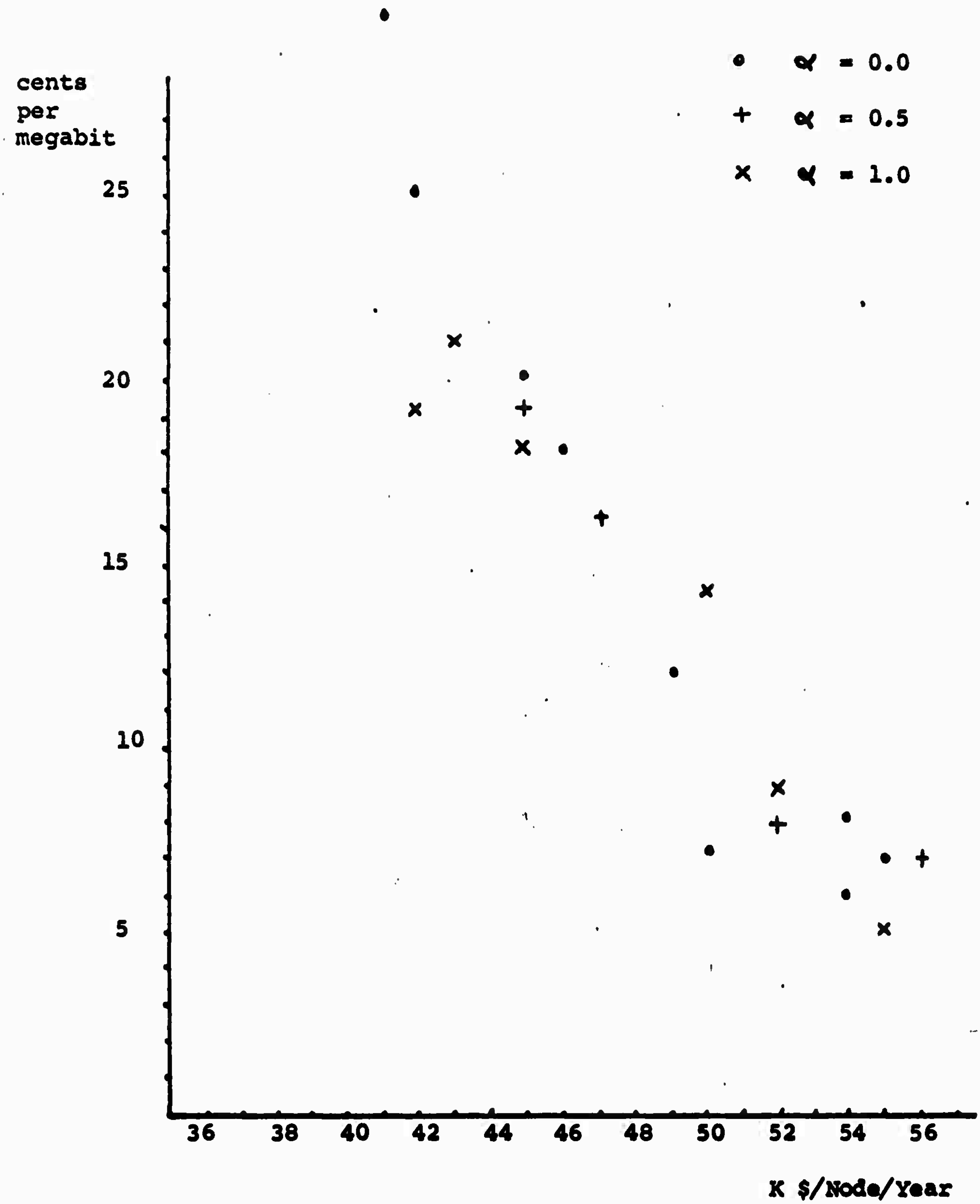

K Bits/
Sec/Node
• α = 0.0
+ α = 0.5
x α = 1.0
25
20
15
10
5
36
38
40
42
44
46
48
50
52
54
56
K $/Node/Year

FIGURE 3.2



cents
per
megabit
25
20
15
10
5
36
38
40
42
44
46
48
50
52
54
56
K $/Node/Year
α = 0.0
α = 0.5
α = 1.0

FIGURE 3.3

Large Network Characteristics

In this section we indicate the results of our study to uncover cost-throughput tradeoffs as a function of the number of nodes in the network. First, we summarize the factors already discussed which influence the network designs.

1. Systems considered contain 20, 40, 60, 80, and 100 IMP's and cover respectively the 10, 18, 26, 32, and 40 largest metropolitan areas in the Continental United States.

2. Required traffic between any two IMP's is independent of distance. From an IMP in city C_i with population P_i to an IMP in city C_j with population P_j, the traffic flow requirement is

$$\frac{K\,(P_i/\,[P_i\,/R\,])\quad(P_j/\,[\,P_j/R\,]\,)}{\sum(P_k\,/\,[P_k\,/\,R\,]\,)}$$

where K is a positive constant and R is the required population per IMP.

3. Messages are assumed to have the same packet structure and formats as in the ARPA Network as described in [1] and [2]. 85% of all messages are assumed to be single packets.

4. In any acceptable network design, a minimum of two nodes and/or links must fail before all paths are broken between any pair of nodes.

5. Throughput is equal to the average number of bits/ second/node which causes an average short message delay of 0.5 seconds.

6. Only hardware presently being used in the ARPA Network is used in any design. Only communication link options presently available to ARPA are used in the design.

An important point which must be emphasized is that the results to follow present a <u>conservative</u> picture of the relationship between cost and throughput. There are two major reasons for this:

1) Each point on each curve represents a feasible network obtained by the computer network design program. Thus, to generate the specified throughput, no greater cost would be involved. However, because of the number of points needed to generate adequate curves, it is prohibitively costly to devote a large amount of computer time to completely optimize each design point. Therefore, if a specific throughput were to be required, a more thorough optimization would be warranted and a lower cost design would be probable.

2) In each design, only the presently available hardware and line options have been allowed. Other equipment is presently being developed and other communication options will be available in the near future. For example, in [1] and [2] we discussed the economics created by using a 108 Kilobit/Second data set. Although this data set has been developed by AT&T, it is not yet a commercial offering. However, the costs involved in building a large computer network would justify the

independent development of such a data set. Moreover, more powerful Interface Message Processors could be developed with existing hardware. Such IMP's might considerably enhance network performance at high data rates.

Because of the above factors, the numerical relationships that follow can be considered to be the result of a worst case analysis. However, we feel that they realistically represent the behavior of large computer networks and that while some reductions in cost or increases in throughput are possible, the fundamental relationship between these quantities is accurately depicted.

Table 3.7 shows cost, throughputs, and other relevant data for a number of 20, 40, 60, 80, and 100 node networks designed by the network optimization program. This data is displayed in Figures 3.4, 3.5, and 3.6. Figure 3.4 indicates the relationship between cost per node and the average number of bits out of each node. In the figure, the location of a point corresponding to an i x 10 node network is indicated by the numeral i. In a similar manner, Figure 3.5 shows the tradeoffs between cost per node and cost per megabit of transmitted data.

In Figure 3.6, the average number of bits out of each node is taken as a parameter. In this figure, the abscissa corresponds to the number of nodes in the network while the ordinate represents the cost per node. The number attached to each point is the average output per node for that network.

TABLE 3.7

Number of Nodes	Yearly Cost (M$)	Yearly Cost per Node (K$)	Total KBits Per Second	KBits per Second per Node	Cost per Megabit of Data at 24 hrs/day (cents)
	0.66	33.0	62	3.1	33.7
	0.79	39.5	157	7.8	16.0
	0.96	48.2	195	9.7	15.7
	1.01	50.7	208	10.4	15.5
20	1.08	54.2	278	13.9	12.4
	1.33	66.7	452	22.6	9.4
	1.36	68.0	505	25.2	8.6
	1.29	32.2	104	2.6	39.3
40	1.70	42.7	304	7.6	17.8
	2.05	51.4	492	12.3	13.2
	2.53	63.3	750	18.7	10.7
	2.95	73.7	903	22.6	10.4
	2.25	37.5	167	2.8	42.7
	2.89	48.1	405	6.8	22.6
60	3.23	53.8	843	14.0	12.2
	4.42	73.7	1035	17.2	13.6
	5.15	85.9	1378	23.0	11.9
	2.60	32.5	133	1.7	61.9
	2.92	36.4	244	3.0	38.0
	3.11	38.9	326	4.1	30.2
80	4.49	56.2	865	10.8	16.5
	5.24	65.4	1123	14.0	14.8
	6.30	78.7	1439	18.0	13.4
	7.40	92.5	2007	25.1	11.7
	3.29	32.0	157	1.6	64.5
	3.66	36.6	386	3.9	30.0
	4.25	42.5	452	4.5	29.8
100	4.88	48.8	829	8.3	18.9
	6.11	61.1	1303	13.0	14.9
	7.12	71.2	1597	16.0	14.1
	7.30	73.0	1719	17.2	13.5
	7.44	74.4	1924	19.2	12.3
	7.54	75.4	2014	20.1	11.9
	7.59	75.9	2166	21.7	11.1
	7.79	77.9	2370	23.7	10.4

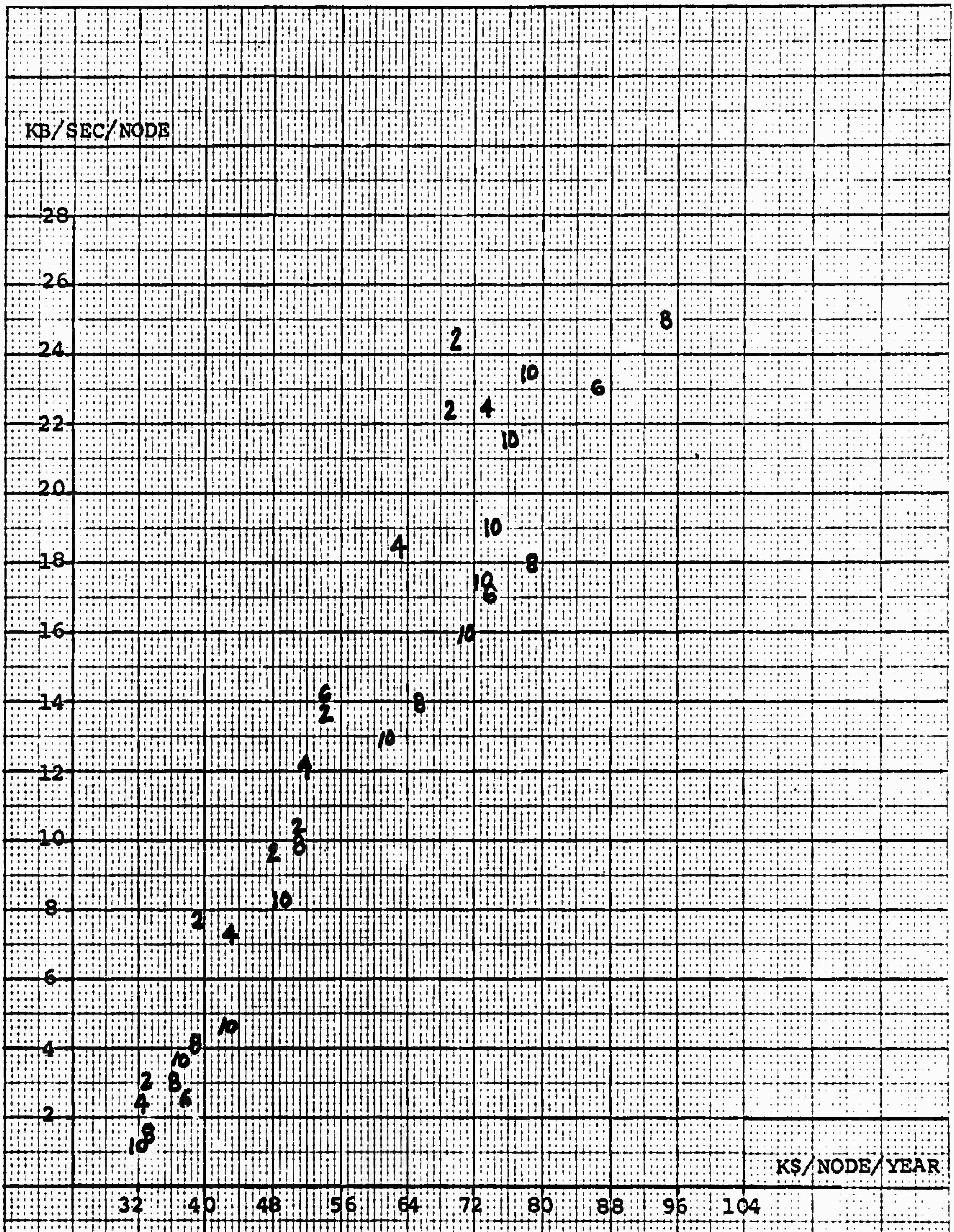


FIGURE 3.4

BEE 20x20 TO INCH

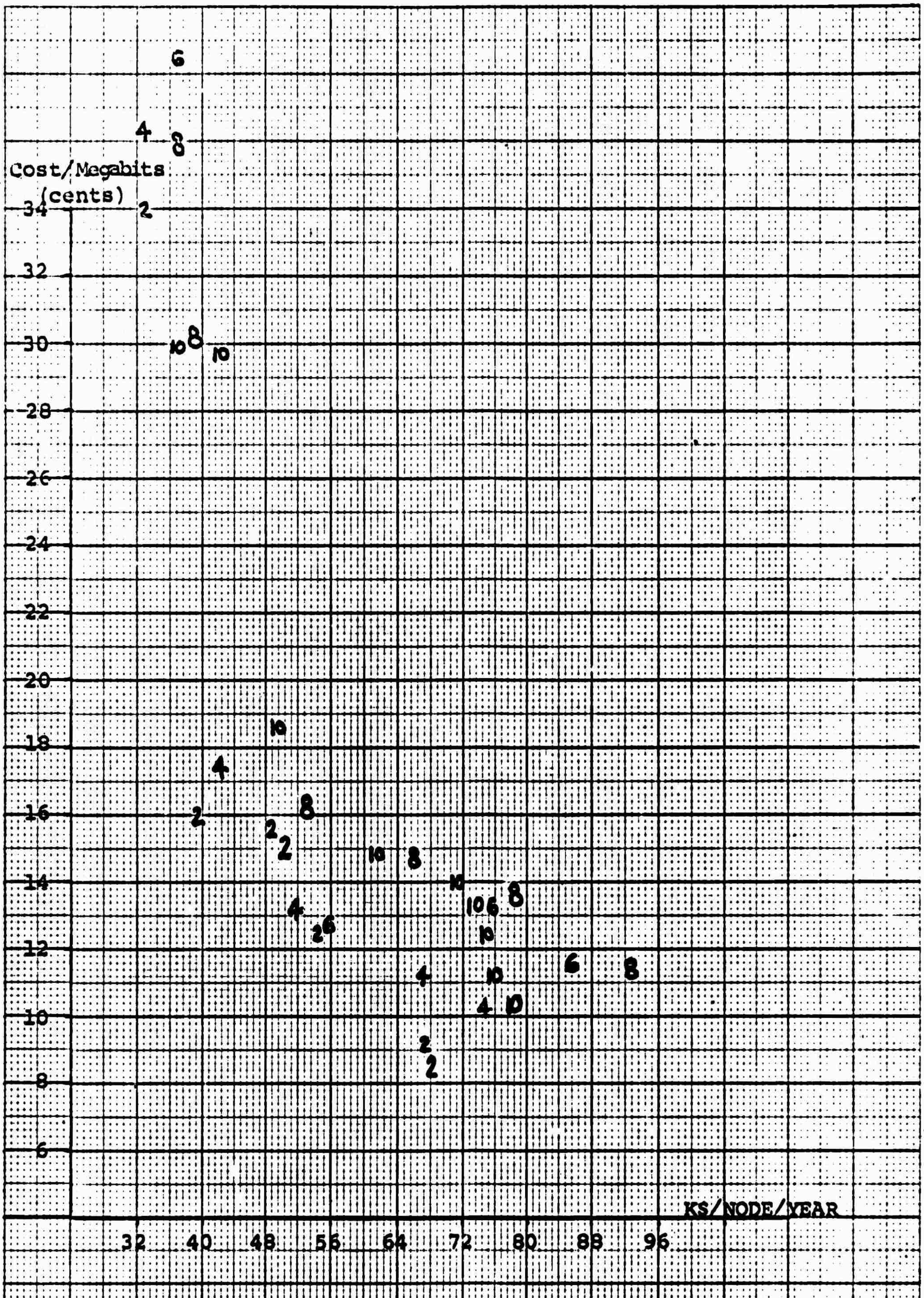


FIGURE 3.5

SEE 20X20 TO INCH

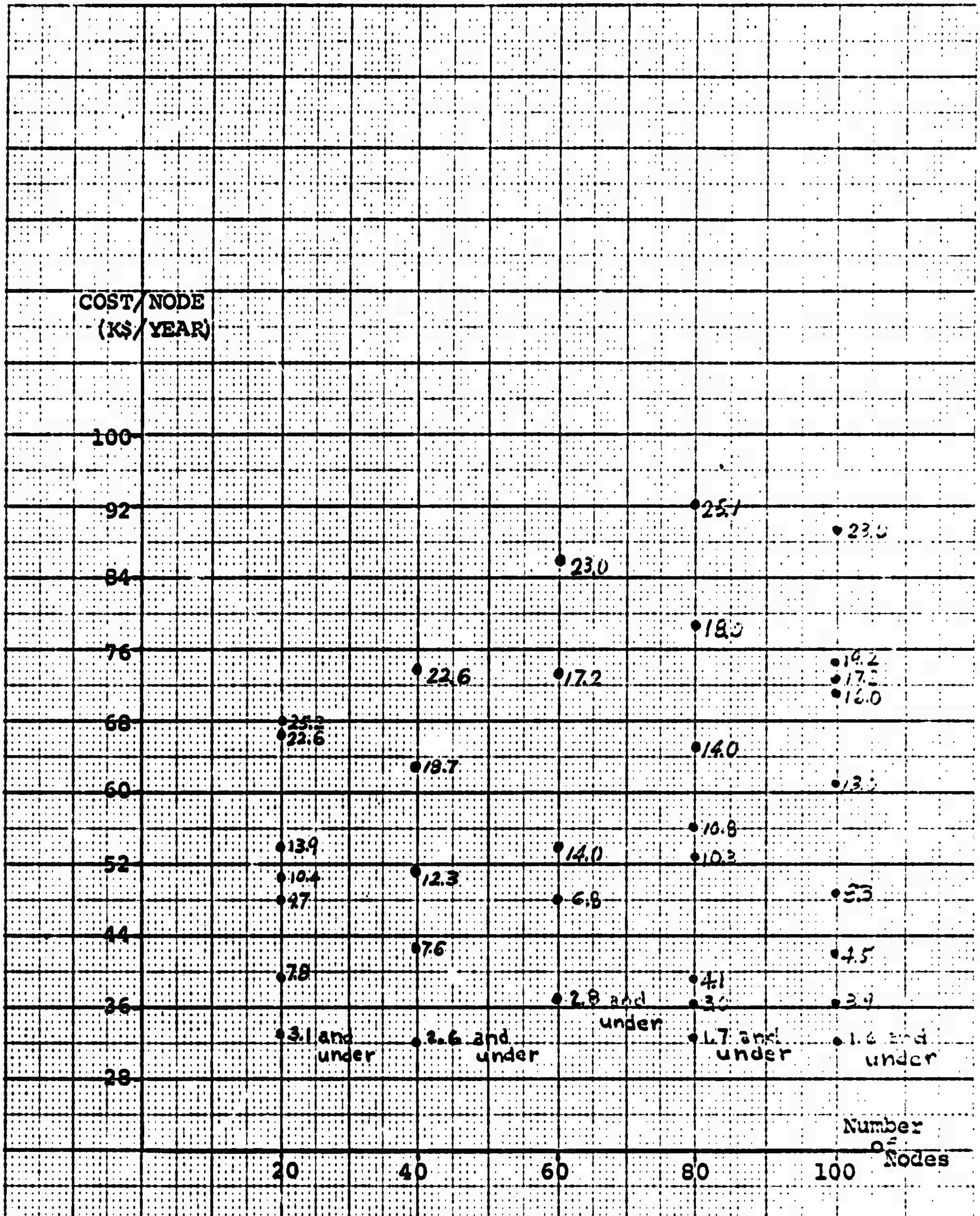
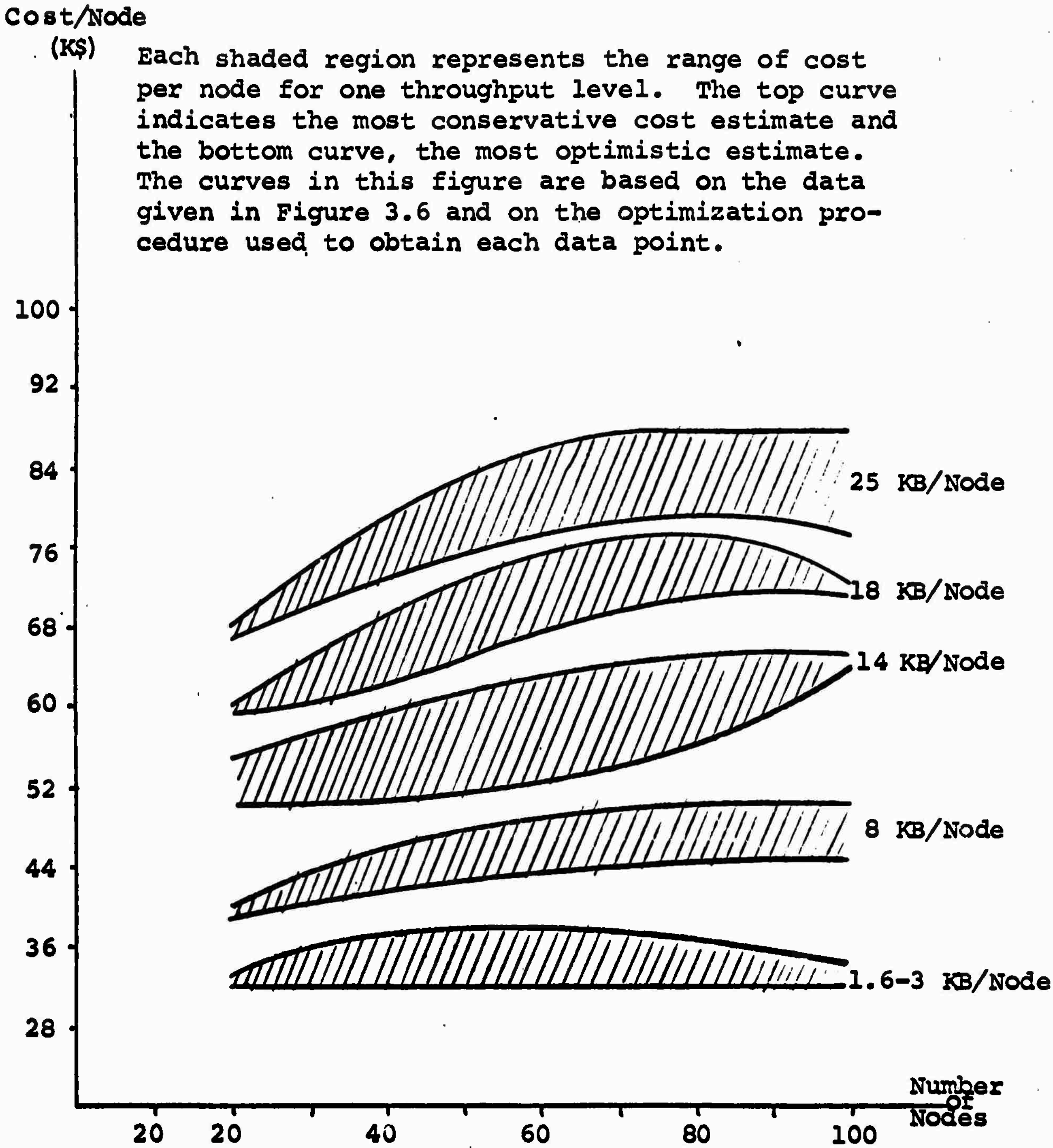

COST/NODE
(K$/YEAR)
100
92
84
76
68
60
52
44
36
28
20
40
60
80
100
Number of Nodes
3.1 and under
2.6 and under
2.8 and under
1.7 and under
and under

FIGURE 3.6

Figure 3.7 shows regions for various output levels as a function of number of nodes and cost per node. Figures 3.6 and 3.7 clearly indicate trends in network performance and economy. At low throughputs (3000 bps or less), within the range of the sizes considered, the larger networks are more economical than the smaller networks. This is because there is a minimum cost required to construct a two connected network, independent of throughput. The minimum cost networks for 20 and 40 node systems result in throughputs of approximately 3000 bps and so if less than that throughput is required, the full cost is still applicable. The larger networks introduce economies of scale which allow more efficient sharing of capacity. Thus a throughput per node of, say, 1500 bps per node can be obtained more economically for a 100 node network than for a 40 node network.

At intermediate and moderately high output levels (5000-15000 bps per node), the larger networks appear to be nearly as economical as the smaller networks. However, since any network would require certain overall fixed project and management costs, operating with a larger number of nodes would reduce the total cost per node for the system.

At very high output levels, (18000 bps and above) the larger networks seem to be somewhat less efficient than the smaller ones. There are several possible reasons for this. For example, the 0.5 second average time delay constraint becomes more difficult to meet with low capacity lines. Long high capacity 230 KB lines



Cost/Node
(K$)
Each shaded region represents the range of cost per node for one throughput level. The top curve indicates the most conservative cost estimate and the bottom curve, the most optimistic estimate. The curves in this figure are based on the data given in Figure 3.6 and on the optimization procedure used to obtain each data point.
100
92
84
76
68
60
52
44
36
28
25 KB/Node
18 KB/Node
14 KB/Node
8 KB/Node
1.6-3 KB/Node
20
20
40
60
80
100
Number of Nodes

FIGURE 3.7

are very uneconomical when compared to 50 KB lines. (For example, a 2500 mile 230 KB line costs more than five 50 KB lines.) The IMP configuration allows only five or six output lines, and consequently the designs are forced to contain a number of costly 230 KB lines rather than more economical combinations. Finally, the present line and IMP options do not allow very high rate (400 KB or more) low cost lines that are presently being developed. Such lines (and IMP's capable of handling the required data rates) would introduce substantial economies of scale.

In summary, using equipment designed for essentially low or intermediate rate traffic, the larger networks can provide service at least as economically as the smaller ones, except at very high throughputs. The decreases in efficiency at higher throughputs seem to be caused by the limitations of the equipment used in the designs. If more suitable equipment, which is either available now or under development, is utilized in the designs, large networks should be more economical than the smaller ones. The precise tradeoffs that occur in such cases will be the subject of continuing study by the Network Analysis Corporation.

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13. ABSTRACT

This report discusses the relationship between traffic, routing, throughput and cost in store-and-forward computer networks. A powerful set of computer programs to optimize cost and performance are described and the results of a study to derive estimates of optimum performance for specified networks are discussed. The tradeoffs between cost and throughput as a function of the number of nodes in the network are displayed, and the substantial cost advantages of large computer-communication networks demonstrated.

14. KEY WORDS

Computer networks, routing, time delay, throughput, cost, large networks, ARPA Computer Network, store-and-forward networks.

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